US010174678B2

(12) **United States Patent**
Schwarz et al.

(10) **Patent No.: US 10,174,678 B2**
(45) **Date of Patent: Jan. 8, 2019**

(54) **BOWED ROTOR START USING DIRECT TEMPERATURE MEASUREMENT**

(71) Applicant: **United Technologies Corporation**, Farmington, CT (US)

(72) Inventors: **Frederick M. Schwarz**, Glastonbury, CT (US); **Amy R. Grace**, Ellington, CT (US)

(73) Assignee: **UNITED TECHNOLOGIES CORPORATION**, Farmington, CT (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 246 days.

(21) Appl. No.: **15/042,377**

(22) Filed: **Feb. 12, 2016**

(65) **Prior Publication Data**

US 2017/0234230 A1 Aug. 17, 2017

(51) **Int. Cl.**

F02C 7/26	(2006.01)
F02C 7/268	(2006.01)
F01D 25/36	(2006.01)
F02C 3/04	(2006.01)
F02C 9/00	(2006.01)
F01D 19/02	(2006.01)
G01H 1/00	(2006.01)

(52) **U.S. Cl.**

CPC ***F02C 7/26*** (2013.01); ***F01D 19/02*** (2013.01); ***F01D 25/36*** (2013.01); ***F02C 3/04*** (2013.01); ***F02C 7/268*** (2013.01); ***F02C 9/00*** (2013.01); ***G01H 1/003*** (2013.01); *F05D 2220/323* (2013.01); *F05D 2260/85* (2013.01); *F05D 2260/941* (2013.01); *F05D 2270/54* (2013.01)

(58) **Field of Classification Search**

CPC .. F02C 7/268; F02C 7/27; F02C 7/272; F02C 7/275; F02C 7/277; F02C 3/107; F02C 9/00; F01D 19/02; F05D 2260/85; F05D 2270/021; F05D 2270/114; F05D 2270/304; F05D 2270/334

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,951,875	A	3/1934	Laabs
2,617,253	A	11/1952	Fusner et al.
2,962,597	A	11/1960	Evans

(Continued)

FOREIGN PATENT DOCUMENTS

EP	1396611	3/2004
EP	1533479 A2	5/2005

(Continued)

OTHER PUBLICATIONS

U.S. Appl. No. 15/042,331 Non-Final Office Action dated Sep. 9, 2016, 37 pages.

(Continued)

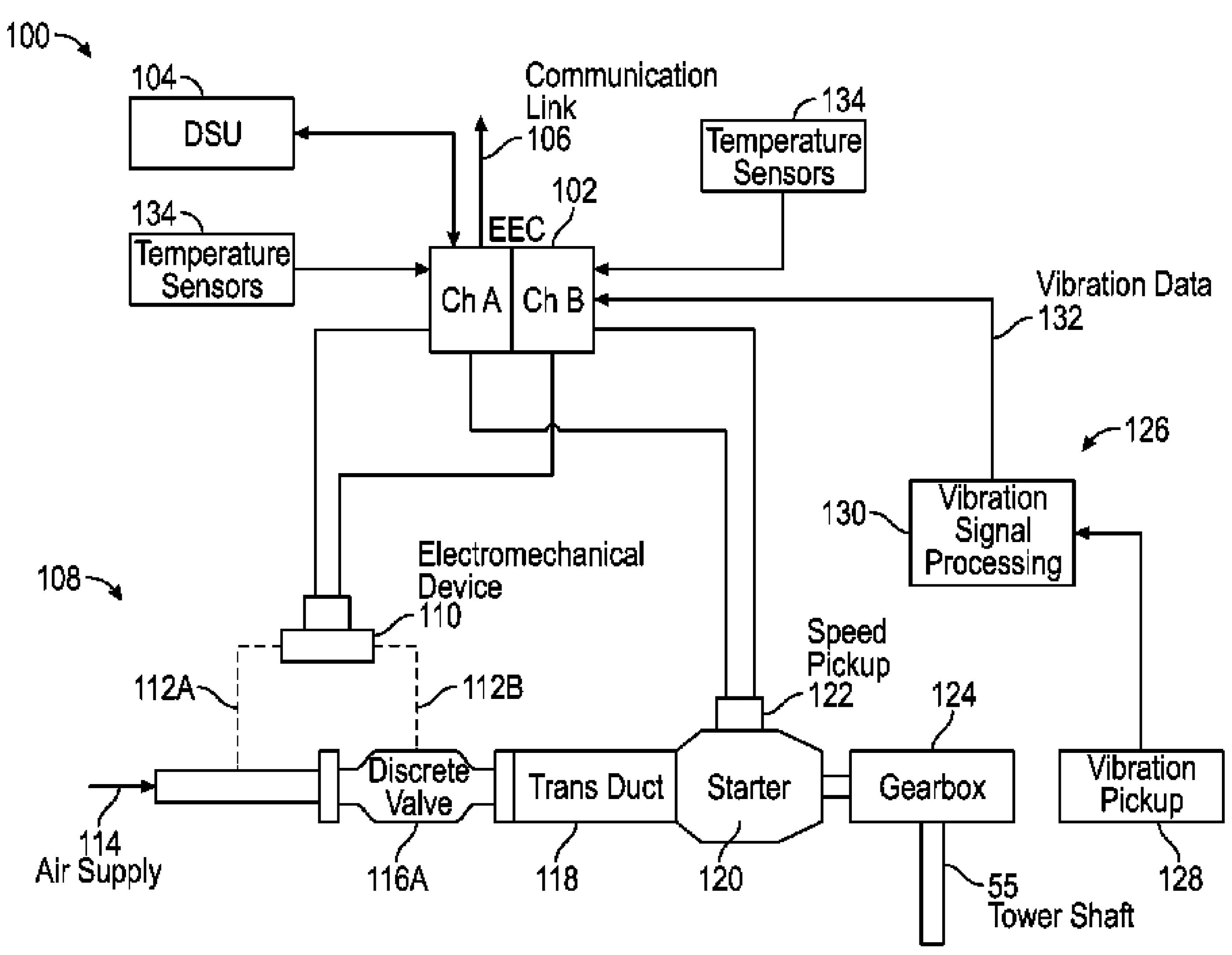
Primary Examiner — Steven Sutherland

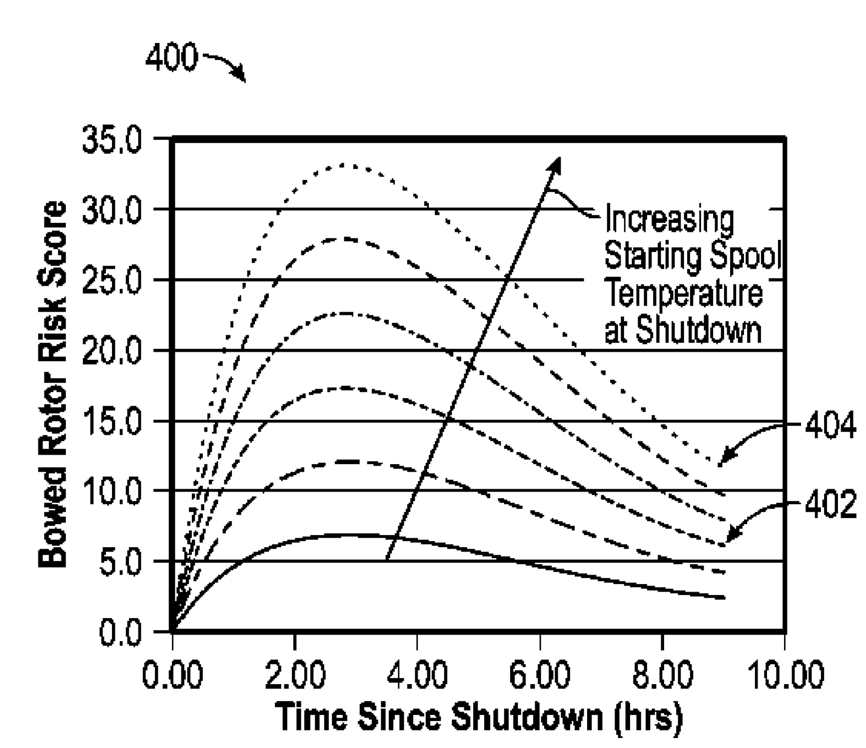
(74) *Attorney, Agent, or Firm* — Cantor Colburn LLP

(57) **ABSTRACT**

A bowed rotor start mitigation system for a gas turbine engine is provided. The bow rotor start mitigation system includes a controller operable to receive a speed input indicative of a rotor speed of the gas turbine engine and a measured temperature of the gas turbine engine. The controller is further operable to drive motoring of the gas turbine engine by oscillating the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated.

20 Claims, 8 Drawing Sheets





(56) **References Cited**

U.S. PATENT DOCUMENTS

3,057,155	A	10/1962	Rizk
3,151,452	A	10/1964	Bunger et al.
3,290,709	A	12/1966	Whitenack, Jr. et al.
3,360,844	A	1/1968	Wonneman
3,764,815	A	10/1973	Habock et al.
3,793,905	A	2/1974	Black et al.
3,898,439	A	8/1975	Reed et al.
3,951,008	A	4/1976	Schneider et al.
4,044,550	A	8/1977	Vermilye
4,069,424	A	1/1978	Burkett
4,120,159	A	10/1978	Matsumoto et al.
4,144,421	A	3/1979	Sakai
4,302,813	A	11/1981	Kurihara et al.
4,353,604	A	10/1982	Dulberger et al.
4,380,146	A	4/1983	Yannone et al.
4,426,641	A	1/1984	Kurihara et al.
4,435,770	A	3/1984	Shiohata et al.
4,437,163	A	3/1984	Kurihara et al.
4,453,407	A	6/1984	Sato et al.
4,485,678	A	12/1984	Fanuele
4,488,240	A	12/1984	Kapadia et al.
4,496,252	A	1/1985	Horler et al.
4,598,551	A	7/1986	Dimitroff, Jr. et al.
4,627,234	A	12/1986	Schuh
4,642,782	A	2/1987	Kemper et al.
4,669,893	A	6/1987	Chalaire et al.
4,713,985	A	12/1987	Ando
4,733,529	A	3/1988	Nelson et al.
4,747,270	A	5/1988	Klie et al.
4,854,120	A	8/1989	Nelson et al.
4,979,362	A	12/1990	Vershure, Jr.
5,103,629	A	4/1992	Mumford et al.
5,123,239	A	6/1992	Rodgers
5,127,220	A	7/1992	Jesrai et al.
5,174,109	A	12/1992	Lampe
5,184,458	A	2/1993	Lampe et al.
5,201,798	A	4/1993	Hogan
5,349,814	A	9/1994	Ciokajlo et al.
6,146,090	A	11/2000	Schmidt
6,168,377	B1	1/2001	Wolfe et al.
6,190,127	B1	2/2001	Schmidt
6,318,958	B1	11/2001	Giesler et al.
6,478,534	B2	11/2002	Bangert et al.
6,498,978	B2	12/2002	Leamy et al.
6,517,314	B1	2/2003	Burnett et al.
6,558,118	B1	5/2003	Brisson et al.
6,681,579	B2	1/2004	Lane et al.
6,762,512	B2	7/2004	Nelson
7,104,072	B2	9/2006	Thompson
7,133,801	B2	11/2006	Song
7,409,319	B2	8/2008	Kant et al.
7,428,819	B2	9/2008	Cataldi et al.
7,507,070	B2	3/2009	Jones
7,543,439	B2	6/2009	Butt et al.
7,587,133	B2	9/2009	Franke et al.
7,742,881	B2	6/2010	Muralidharan et al.
7,798,720	B1	9/2010	Walsh
7,909,566	B1	3/2011	Brostmeyer
7,972,105	B2	7/2011	Dejoris et al.
8,090,456	B2	1/2012	Karpman et al.
8,291,715	B2	10/2012	Libera et al.
8,306,776	B2	11/2012	Ihara et al.
8,770,913	B1	7/2014	Negron et al.
8,776,530	B2	7/2014	Shirooni et al.
8,820,046	B2	9/2014	Ross et al.
8,918,264	B2	12/2014	Jegu et al.
9,086,018	B2	7/2015	Winston et al.
9,121,309	B2	9/2015	Geiger
9,664,070	B1	5/2017	Clauson et al.
9,699,833	B2	7/2017	Broughton et al.
2002/0173897	A1	11/2002	Leamy et al.
2003/0145603	A1	8/2003	Reed et al.
2004/0065091	A1	4/2004	Anderson
2004/0131138	A1	7/2004	Correia et al.
2006/0032234	A1	2/2006	Thompson
2006/0260323	A1	11/2006	Moulebhar
2007/0031249	A1	2/2007	Jones
2008/0072568	A1	3/2008	Moniz et al.
2009/0246018	A1	10/2009	Kondo et al.
2009/0301053	A1	12/2009	Geiger
2009/0314002	A1	12/2009	Libera et al.
2010/0095791	A1	4/2010	Galloway
2010/0132365	A1	6/2010	Labala
2010/0293961	A1	11/2010	Tong et al.
2010/0326085	A1	12/2010	Veilleux
2011/0077783	A1	3/2011	Karpman et al.
2011/0146276	A1	6/2011	Sathyanarayana et al.
2011/0153295	A1	6/2011	Yerramalla et al.
2011/0296843	A1	12/2011	Lawson, Jr.
2012/0031067	A1	2/2012	Sundaram et al.
2012/0240591	A1	9/2012	Snider et al.
2012/0266601	A1	10/2012	Miller
2012/0316748	A1	12/2012	Jegu et al.
2013/0031912	A1	2/2013	Finney et al.
2013/0091850	A1	4/2013	Francisco
2013/0101391	A1	4/2013	Szwedowicz et al.
2013/0134719	A1	5/2013	Watanabe et al.
2013/0251501	A1	9/2013	Araki et al.
2014/0060076	A1	3/2014	Cortelli et al.
2014/0123673	A1	5/2014	Mouze et al.
2014/0199157	A1	7/2014	Haerms et al.
2014/0236451	A1	8/2014	Gerez et al.
2014/0241878	A1	8/2014	Herrig et al.
2014/0271152	A1	9/2014	Rodriguez
2014/0301820	A1	10/2014	Lohse et al.
2014/0318144	A1	10/2014	Lazzeri et al.
2014/0334927	A1	11/2014	Hammerum
2014/0366546	A1	12/2014	Bruno et al.
2014/0373518	A1	12/2014	Manneville et al.
2014/0373552	A1	12/2014	Zaccaria et al.
2014/0373553	A1	12/2014	Zaccaria et al.
2014/0373554	A1	12/2014	Pech et al.
2015/0016949	A1	1/2015	Smith
2015/0115608	A1	4/2015	Draper
2015/0121874	A1	5/2015	Yoshida et al.
2015/0128592	A1	5/2015	Filiputti et al.
2015/0159625	A1	6/2015	Hawdwicke, Jr. et al.
2015/0219121	A1	8/2015	King
2015/0377141	A1	12/2015	Foiret
2016/0236369	A1	8/2016	Baker
2016/0245312	A1	8/2016	Morice
2016/0265387	A1	9/2016	Duong et al.
2016/0288325	A1	10/2016	Naderer et al.
2017/0030265	A1	2/2017	O'Toole et al.
2017/0218848	A1	8/2017	Alstad et al.
2017/0233103	A1	8/2017	Teicholz et al.
2017/0234158	A1	8/2017	Savela
2017/0234166	A1	8/2017	Dube et al.
2017/0234167	A1	8/2017	Stachowiak et al.
2017/0234231	A1	8/2017	Virtue, Jr. et al.
2017/0234232	A1	8/2017	Sheridan et al.
2017/0234233	A1	8/2017	Schwarz et al.
2017/0234235	A1	8/2017	Pech
2017/0234236	A1	8/2017	Feulner et al.
2017/0234238	A1	8/2017	Schwarz et al.
2018/0010480	A1	1/2018	Hockaday et al.

FOREIGN PATENT DOCUMENTS

EP	1862875		12/2007
EP	2006496		12/2008
EP	2305986		4/2011
EP	2363575	A2	9/2011
EP	2871333		5/2015
EP	3051074		8/2016
FR	2933131		1/2010
GB	1374810		11/1974
GB	2117842		10/1983
GB	2218751		11/1989
IN	201408865		5/2015
JP	2002371806		12/2002
JP	2004036414		2/2004
WO	9900585		1/1999
WO	2013007912		1/2013

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

WO	2014152701	9/2014
WO	2015030946	3/2015
WO	2016069303	5/2016

OTHER PUBLICATIONS

EP Application No. 17155584 Extended European Search Report dated Jul. 6, 2017, 9 pages.
EP Application No. 17155601 Extended European Search Report dated Jun. 30, 2017, 7 pages.
EP Application No. 17155612 Extended European Search Report dated Jul. 4, 2017, 8 pages.
EP Application No. 17155613 Extended European Search Report dated Jun. 27, 2017, 10 pages.
EP Application No. 17155683 Extended European Search Report dated Jun. 30, 2017, 8 pages.
EP Application No. 17155687 Extended European Search Report dated Jun. 16, 2017, 9 pages.
EP Application No. 17155698 Extended European Search Report dated Jun. 21, 2017, 9 pages.
EP Application No. 17155721 Extended European Search Report dated Jun. 27, 2017, 8 pages.
EP Application No. 17155793 Extended European Search Report dated Jun. 30, 2017, 10 pages.
EP Application No. 17155798 Extended European Search Report dated Jun. 30, 2017, 9 pages.
EP Application No. 17155807 Extended European Search Report dated Jul. 30, 2017, 8 pages.
Extended European Search Report for Application No. 17179407.6-1610 dated Dec. 5, 2017 (8 pp.).
EP Application No. 17155683 Office Action dated May 22, 2018, 2 pages.

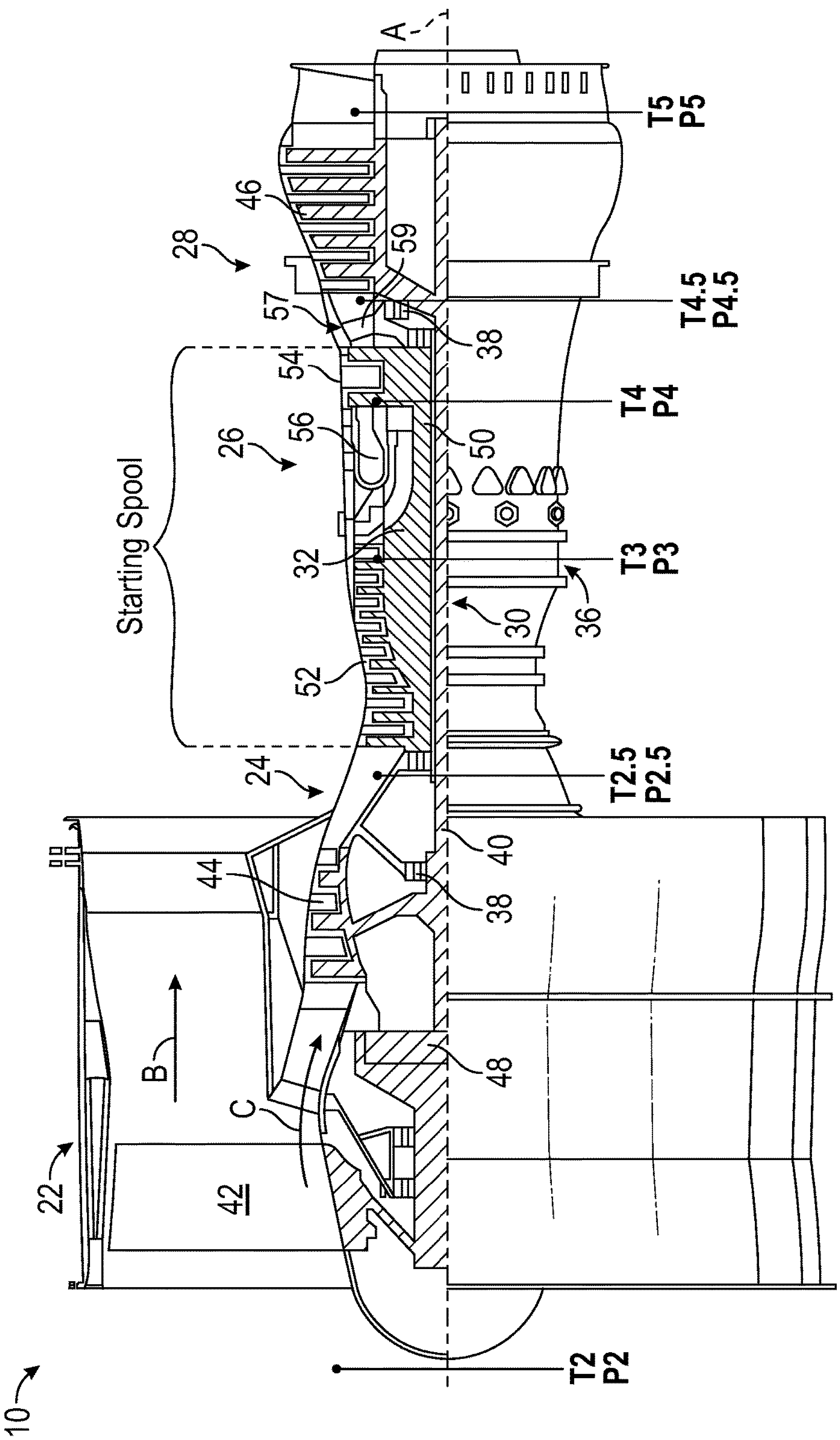

10
22
42
B
C
44
48
38
40
24
T2.5
P2.5
Starting Spool
52
30
36
32
T3
P3
26
56
50
T4
P4
54
57
38
T4.5
P4.5
28
46
59
T5
P5
A
T2
P2

FIG. 1

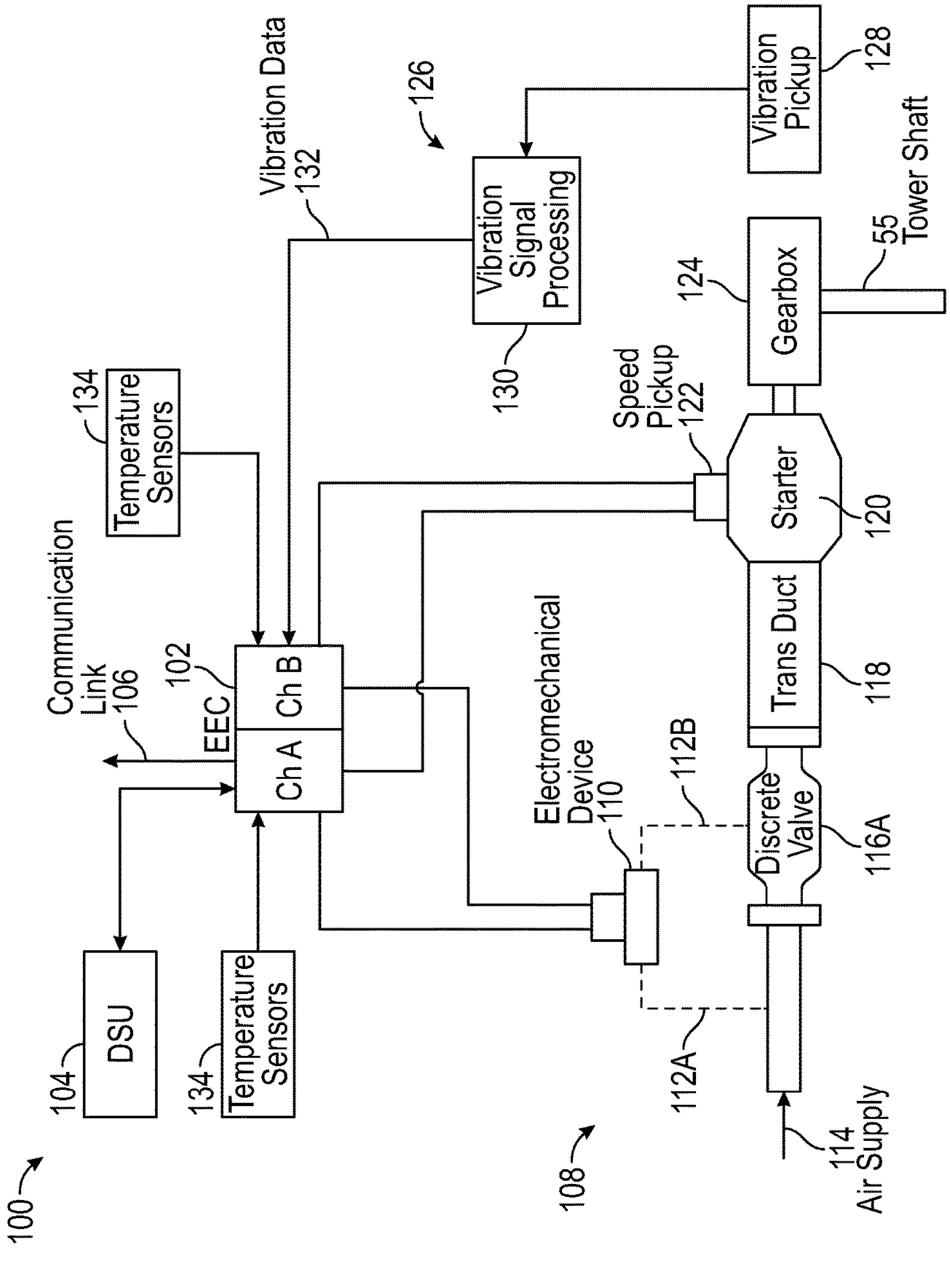

100
DSU
104
Temperature Sensors
134
EEC
Ch A
Ch B
102
Communication Link
106
Temperature Sensors
134
Vibration Data
132
126
Vibration Signal Processing
130
Vibration Pickup
128
Electromechanical Device
110
112A
112B
108
Air Supply
114
Discrete Valve
116A
Trans Duct
118
Starter
120
Speed Pickup
122
Gearbox
124
55
Tower Shaft

FIG. 2

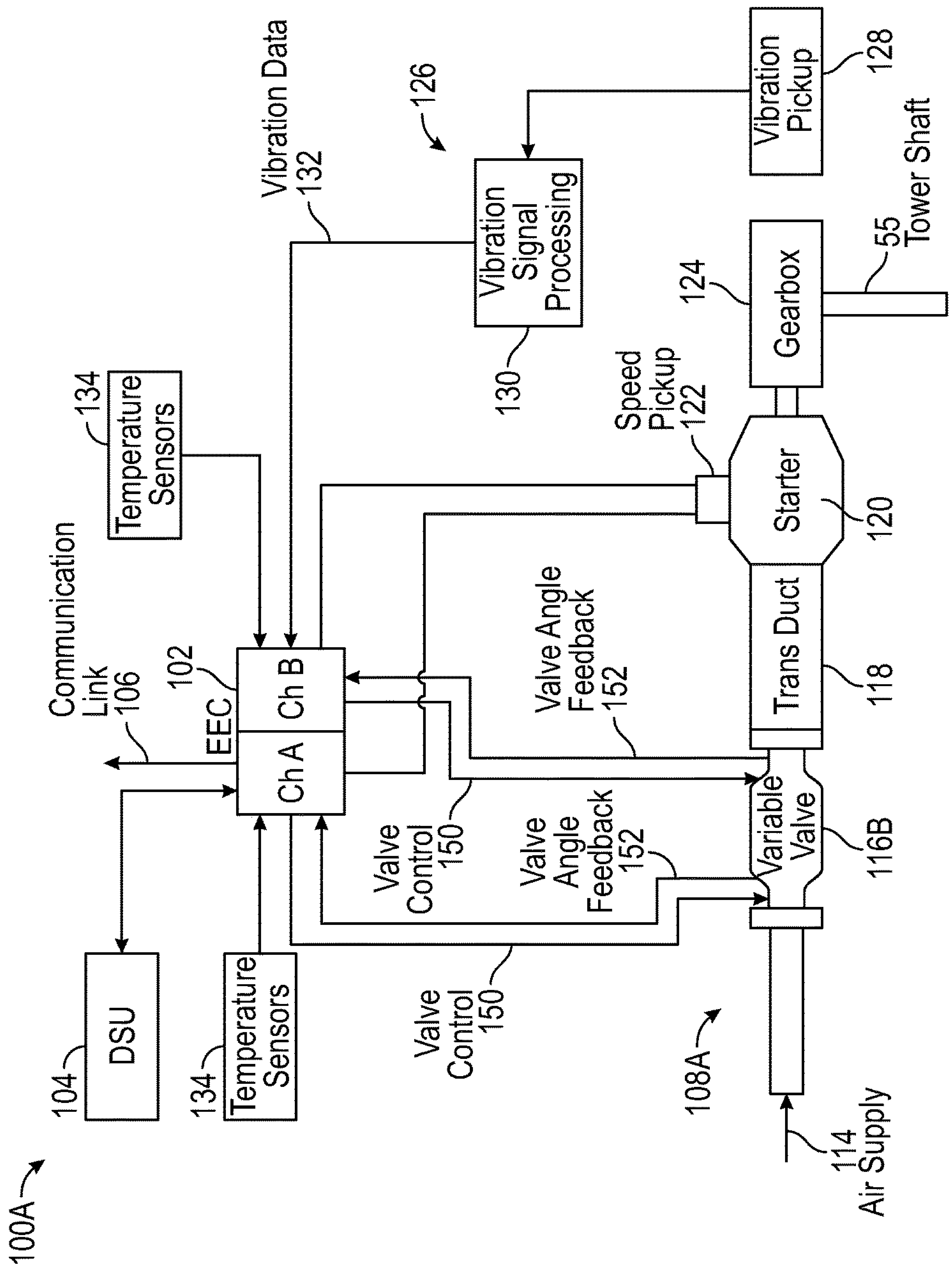

100A
104
DSU
134
Temperature Sensors
Communication Link 106
EEC
102
Ch A
Ch B
134
Temperature Sensors
Vibration Data 132
126
Vibration Signal Processing
130
Vibration Pickup
128
Valve Control 150
Valve Angle Feedback 152
Valve Control 150
Valve Angle Feedback 152
Valve Control 150
Speed Pickup 122
Starter
120
Gearbox
124
55 Tower Shaft
Trans Duct
118
Variable Valve
116B
108A
114 Air Supply

FIG. 3

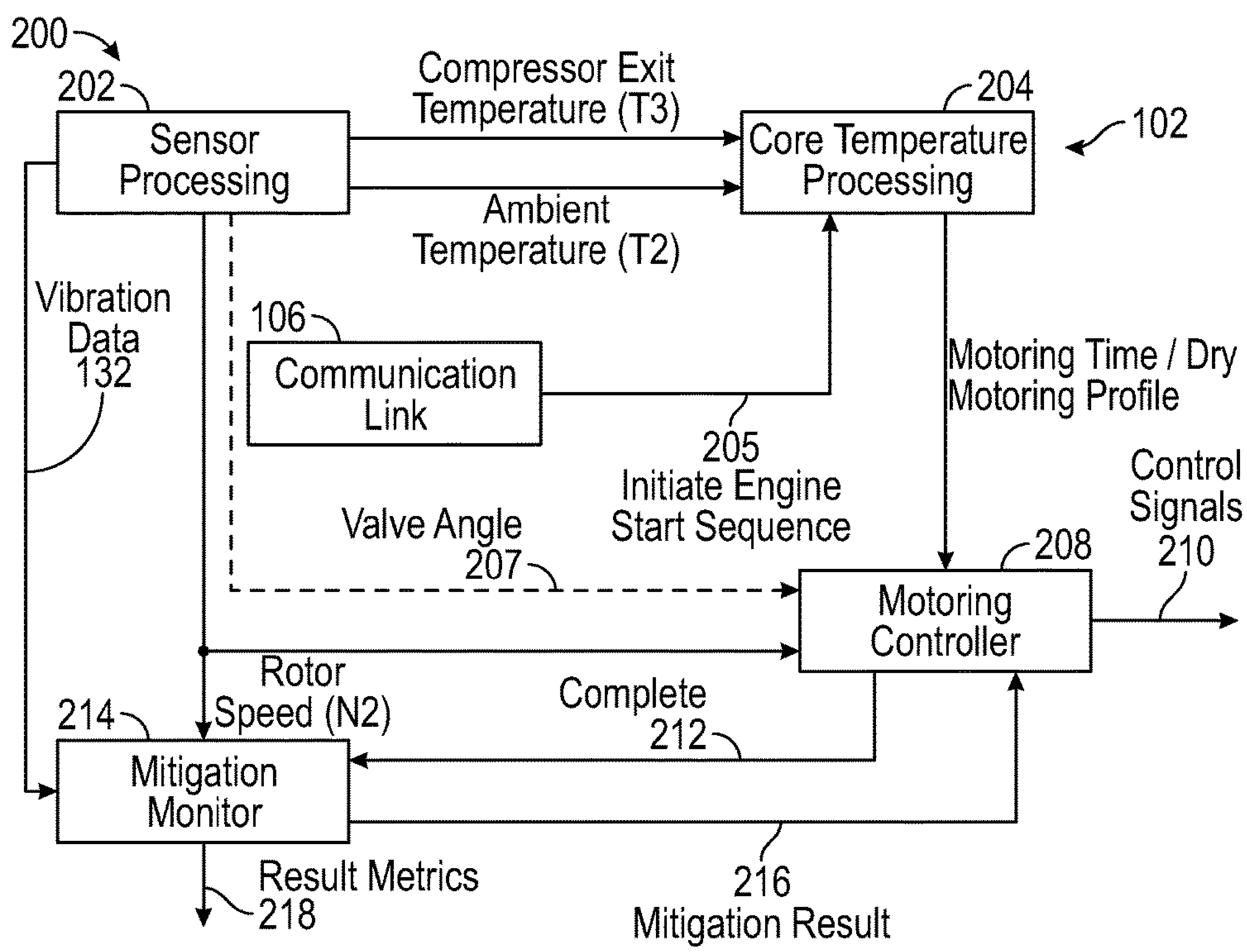

200
202
Sensor Processing
Compressor Exit Temperature (T3)
Ambient Temperature (T2)
204
Core Temperature Processing
102
Vibration Data 132
106
Communication Link
205
Initiate Engine Start Sequence
Motoring Time / Dry Motoring Profile
Control Signals 210
Valve Angle 207
208
Motoring Controller
Rotor Speed (N2)
214
Mitigation Monitor
Complete 212
Result Metrics 218
216
Mitigation Result

FIG. 4

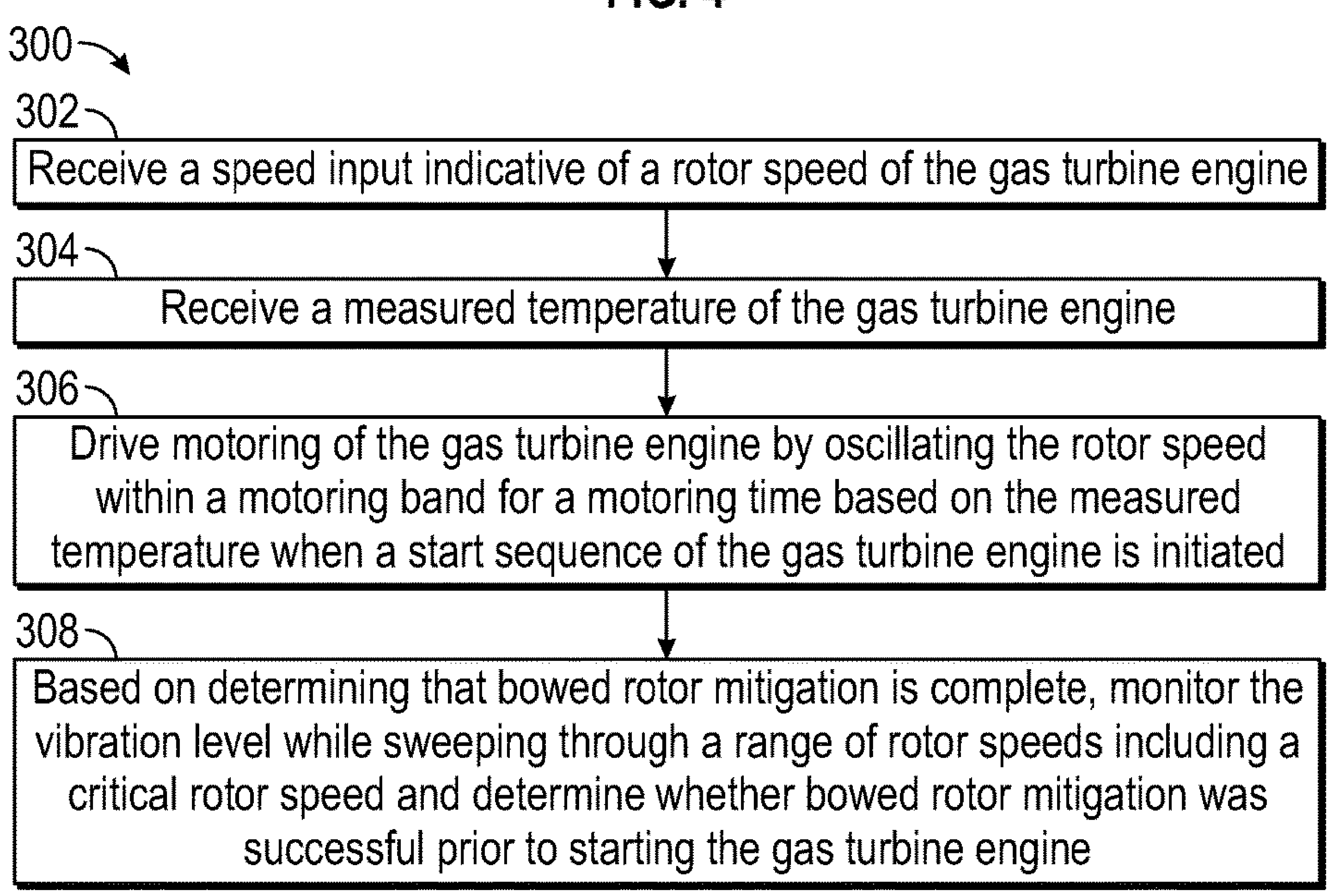

300
302
Receive a speed input indicative of a rotor speed of the gas turbine engine
304
Receive a measured temperature of the gas turbine engine
306
Drive motoring of the gas turbine engine by oscillating the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated
308
Based on determining that bowed rotor mitigation is complete, monitor the vibration level while sweeping through a range of rotor speeds including a critical rotor speed and determine whether bowed rotor mitigation was successful prior to starting the gas turbine engine

FIG. 5

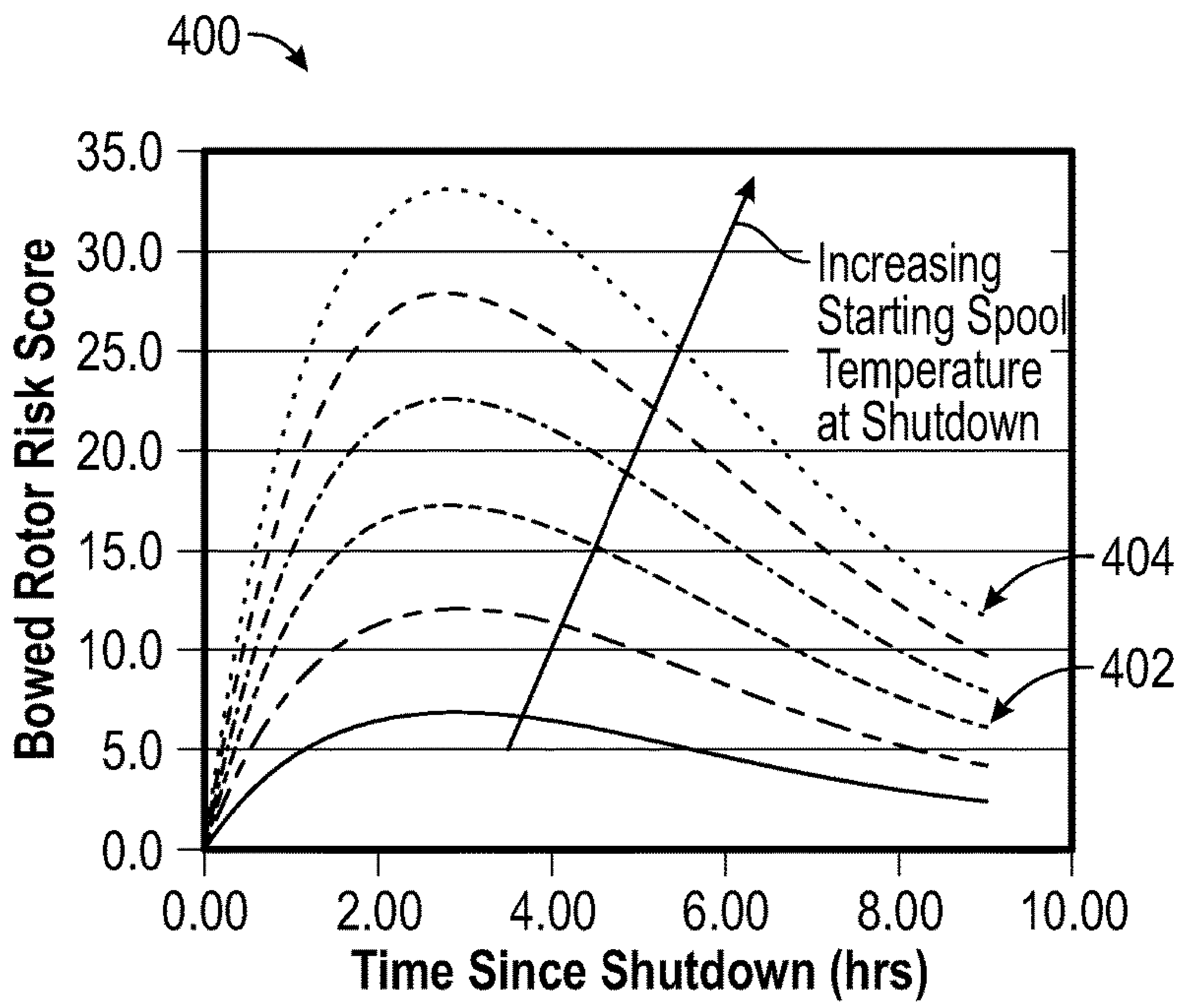

400
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Bowed Rotor Risk Score
Increasing Starting Spool Temperature at Shutdown
404
402
0.00
2.00
4.00
6.00
8.00
10.00
Time Since Shutdown (hrs)

FIG. 6

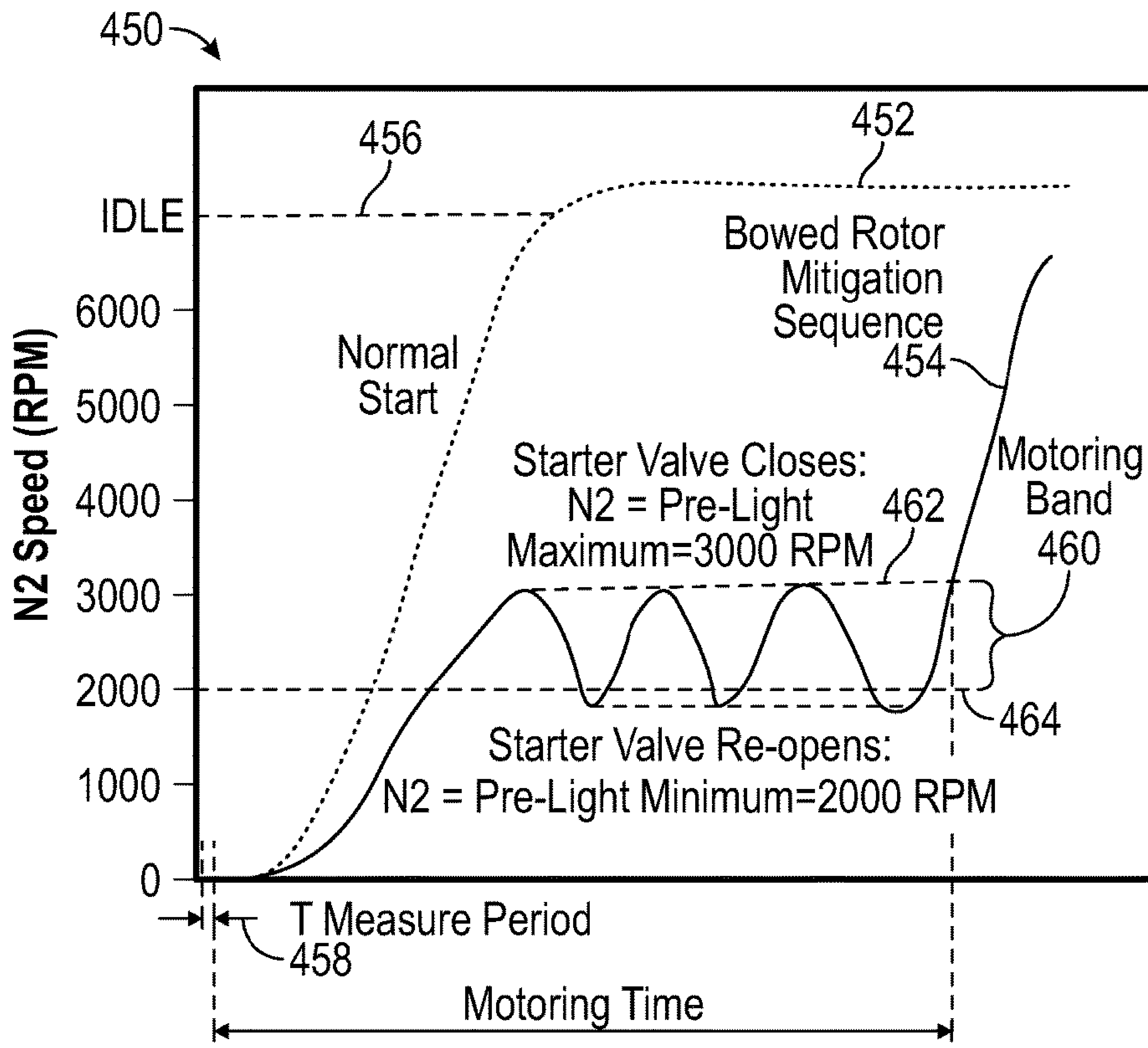

450
456
452
IDLE
6000
5000
4000
3000
2000
1000
0
N2 Speed (RPM)
Normal Start
Bowed Rotor Mitigation Sequence 454
Starter Valve Closes: N2 = Pre-Light Maximum=3000 RPM
462
Motoring Band 460
464
Starter Valve Re-opens: N2 = Pre-Light Minimum=2000 RPM
T Measure Period
458
Motoring Time

FIG. 7

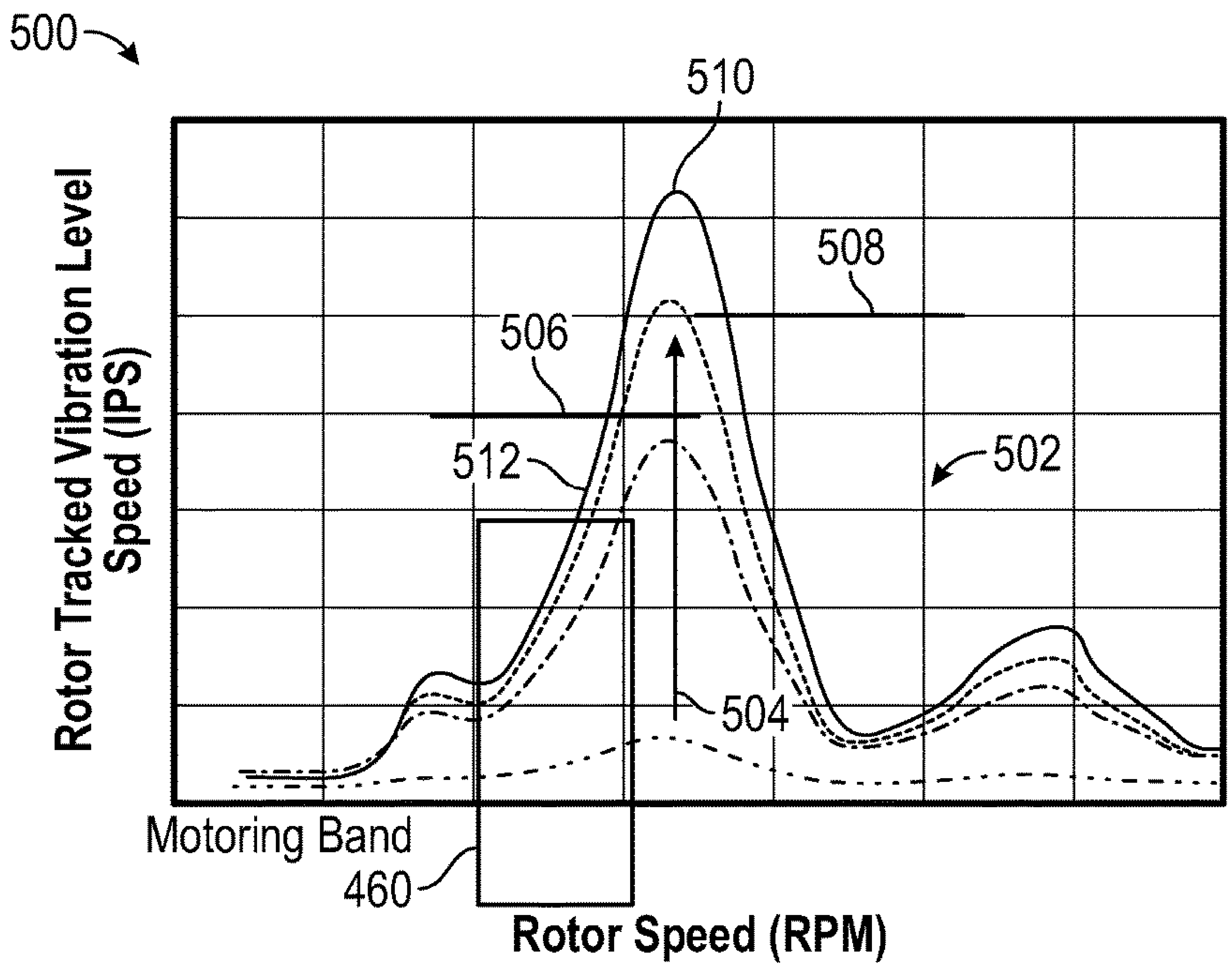

500
510
508
506
512
502
504
Rotor Tracked Vibration Level
Speed (IPS)
Motoring Band
460
Rotor Speed (RPM)

FIG. 8

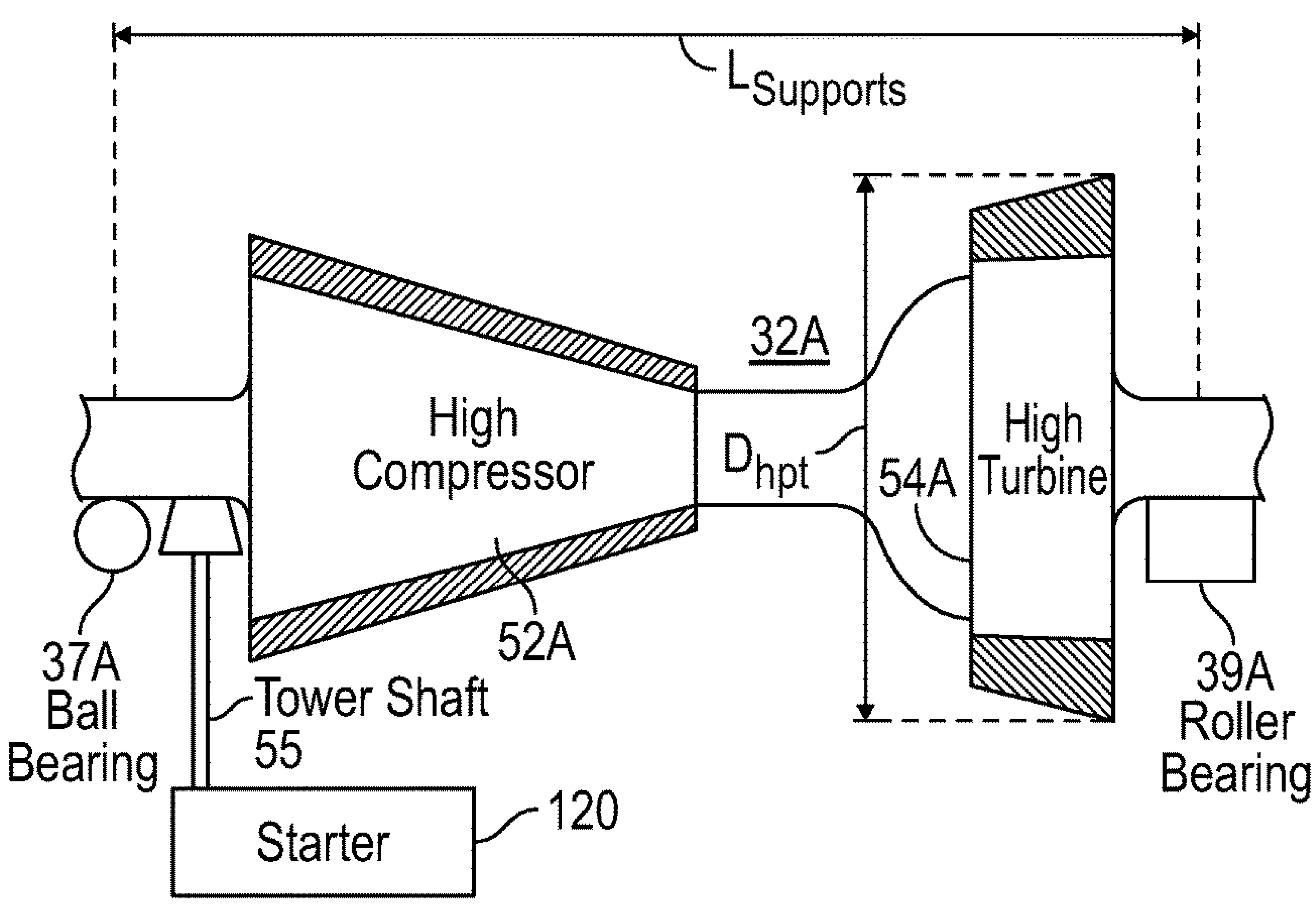
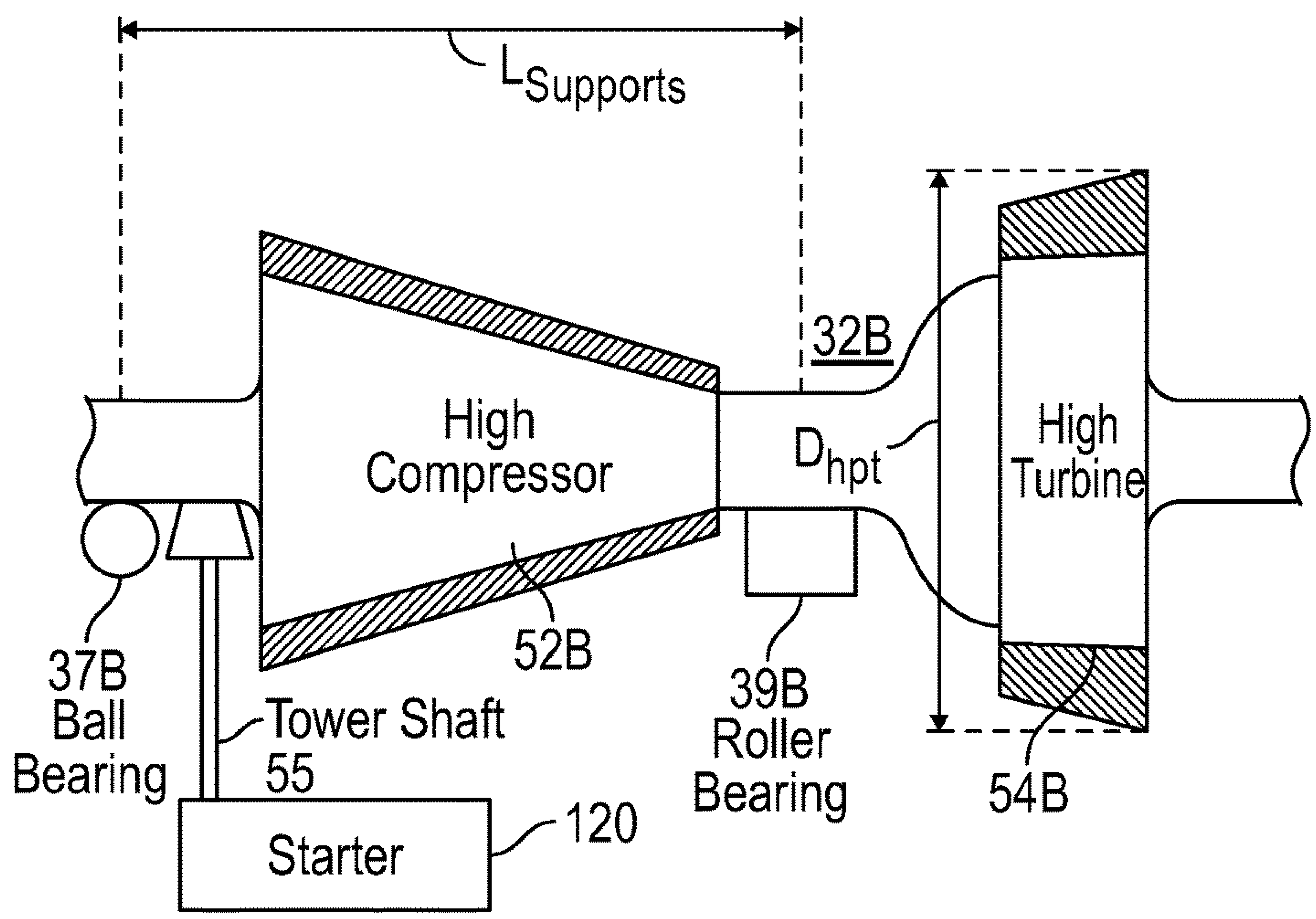
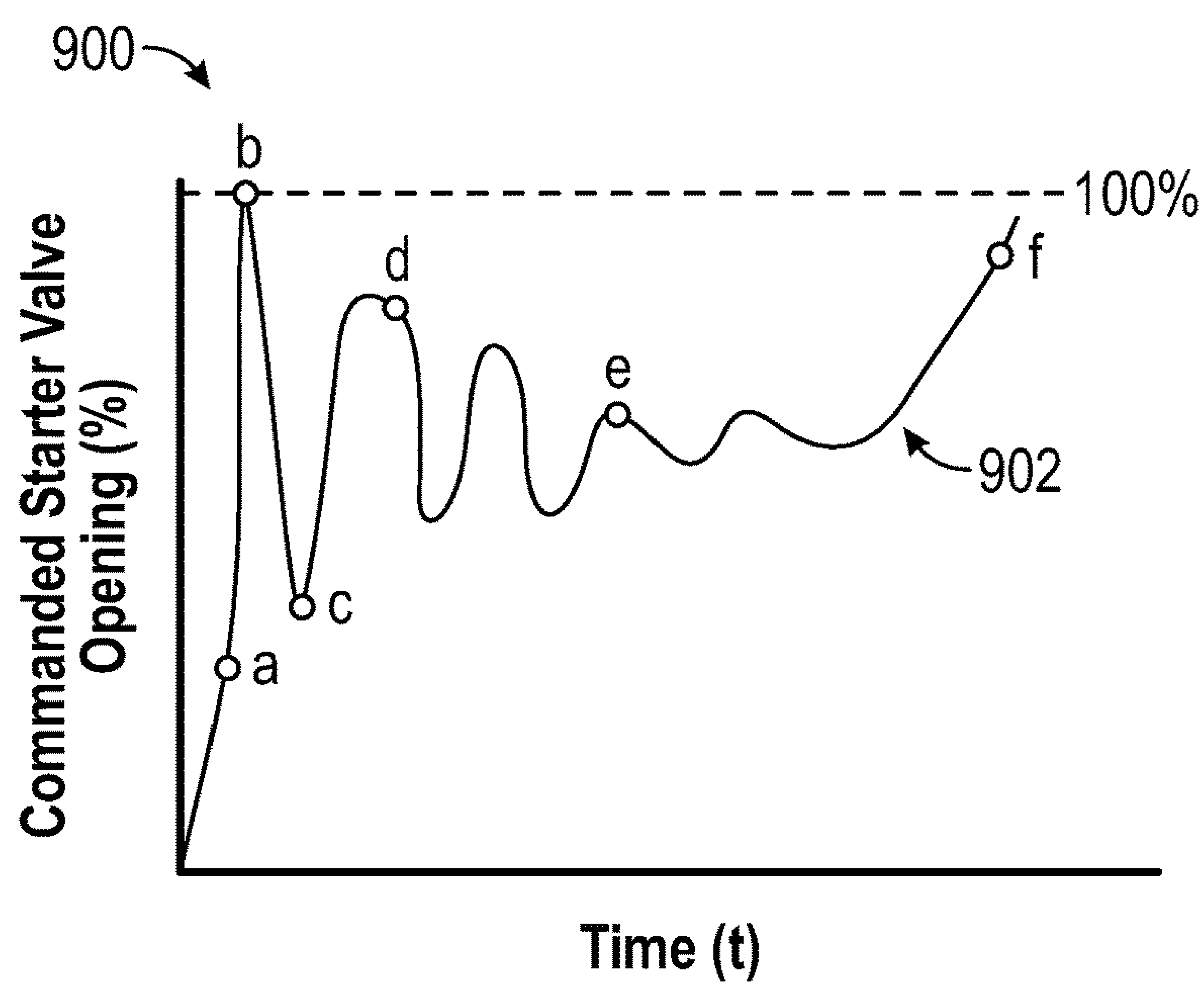

$L_{Supports}$
32A
High
Compressor
D_{hpt}
54A
High
Turbine
52A
37A
Ball
Bearing
Tower Shaft
55
Starter
120
39A
Roller
Bearing

FIG. 9



L Supports
32B
High Compressor
D hpt
High Turbine
37B Ball Bearing
Tower Shaft 55
52B
39B Roller Bearing
54B
Starter
120

FIG. 10



900
b
100%
d
f
e
902
c
a
Commanded Starter Valve Opening (%)
Time (t)

FIG. 11

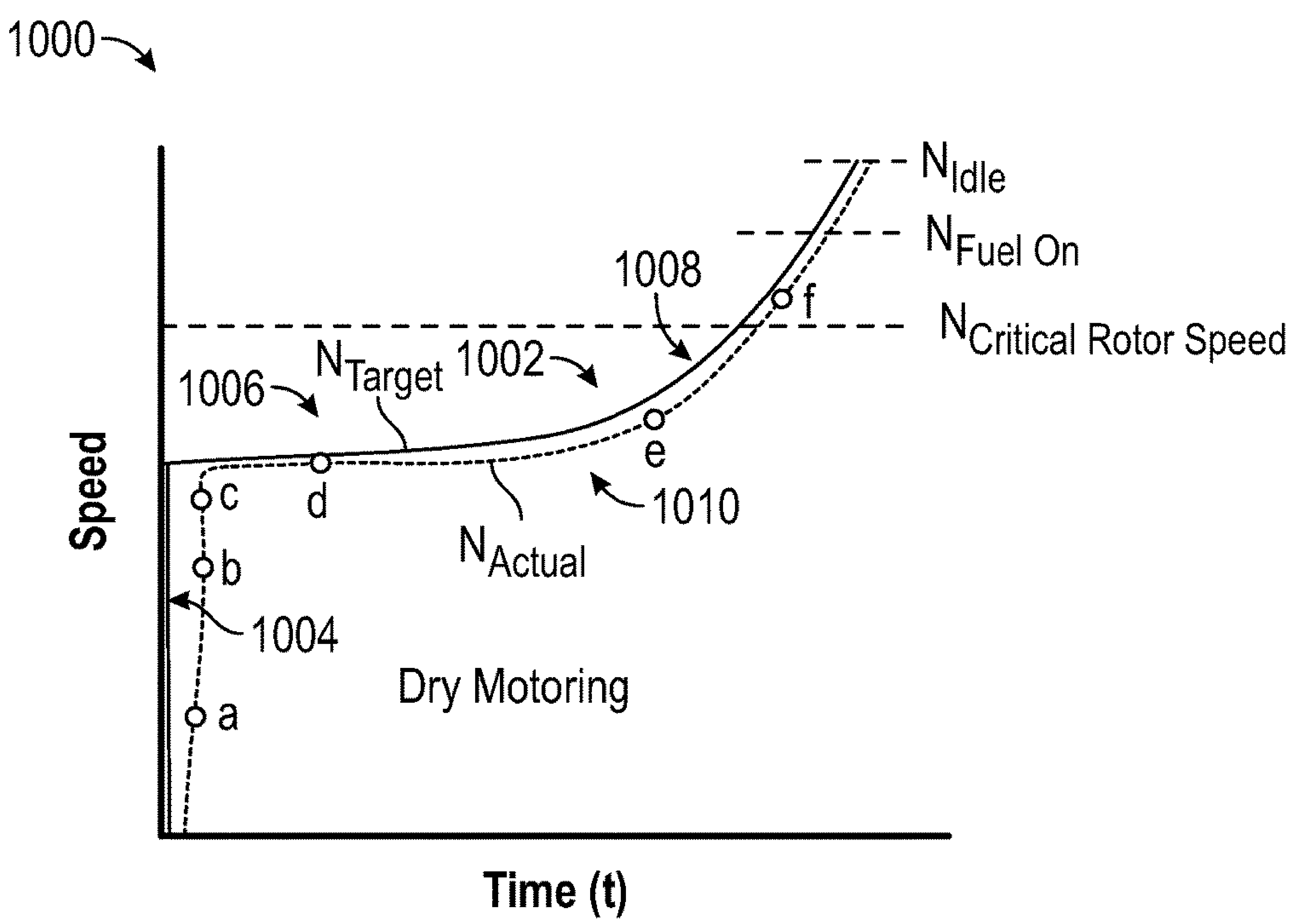

1000
Speed
Time (t)
N_Idle
N_Fuel On
N_Critical Rotor Speed
N_Target
N_Actual
1002
1004
1006
1008
1010
a
b
c
d
e
f
Dry Motoring

FIG. 12

BOWED ROTOR START USING DIRECT TEMPERATURE MEASUREMENT

BACKGROUND

This disclosure relates to gas turbine engines, and more particularly to an apparatus, system and method for mitigating a bowed rotor start condition using direct temperature measurement in a gas turbine engine.

Gas turbine engines are used in numerous applications, one of which is for providing thrust to an airplane. When the gas turbine engine of an airplane has been shut off for example, after an airplane has landed at an airport, the engine is hot and due to heat rise, the upper portions of the engine will be hotter than lower portions of the engine. When this occurs thermal expansion may cause deflection of components of the engine which may result in a "bowed rotor" condition. If a gas turbine engine is in such a "bowed rotor" condition it is undesirable to restart or start the engine.

Accordingly, it is desirable to provide a method and/or apparatus for detecting and preventing a "bowed rotor" condition.

BRIEF DESCRIPTION

In an embodiment, a bowed rotor start mitigation system for a gas turbine engine is provided. The bow rotor start mitigation system includes a controller operable to receive a speed input indicative of a rotor speed of the gas turbine engine and a measured temperature of the gas turbine engine. The controller is further operable to drive motoring of the gas turbine engine by oscillating the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the motoring band includes a range of speeds below a resonance speed of the gas turbine engine.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the measured temperature is adjusted with respect to a measured ambient temperature of the gas turbine engine.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the motoring time is associated with a bowed rotor risk parameter that is determined based on the measured temperature.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the measured temperature is determined based on reading one or more temperature sensors of the gas turbine engine for a predetermined period of time when the start sequence of the gas turbine engine is initiated.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where based on determining that bowed rotor mitigation is complete, the controller is operable to monitor the vibration level while sweeping through a range of rotor speeds including a critical rotor speed and determine whether bowed rotor mitigation was successful prior to starting the gas turbine engine.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments,

further embodiments may include where the measured temperature is determined based on reading data from one or more temperature sensors at station **3** of the gas turbine engine.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the measured temperature is determined based on reading data from one or more temperature sensors at station **4** of the gas turbine engine.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the measured temperature is determined based on reading data from one or more temperature sensors at station **4.5** of the gas turbine engine.

According to an embodiment, a gas turbine engine includes a motoring system operable to drive rotation of the gas turbine engine, a speed pickup, a temperature sensor, and an electronic engine control operable to receive a speed input from the speed pickup indicative of a rotor speed of the gas turbine engine and a measured temperature from the temperature sensor. The electronic engine control is further operable to drive motoring of the gas turbine engine by controlling the motoring system to oscillate the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated.

According to an embodiment, a method of bowed rotor start mitigation for a gas turbine engine includes receiving, by a controller, a speed input indicative of a rotor speed of the gas turbine engine. The controller also receives a measured temperature of the gas turbine engine. The controller drives motoring of the gas turbine engine by oscillating the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated.

A technical effect of the apparatus, systems and methods is achieved by using a start sequence for a gas turbine engine as described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the present disclosure is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features, and advantages of the present disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** is a cross-sectional view of a gas turbine engine;

FIG. **2** is a schematic illustration of a starting system for a gas turbine engine in accordance with an embodiment of the disclosure;

FIG. **3** is a schematic illustration of a starting system for a gas turbine engine in accordance with another embodiment of the disclosure;

FIG. **4** is a block diagram of a system for bowed rotor start mitigation in accordance with an embodiment of the disclosure;

FIG. **5** is a flow chart illustrating a method of bowed rotor start mitigation using direct temperature measurement of a gas turbine engine in accordance with an embodiment of the disclosure;

FIG. **6** is a graph illustrating a bowed rotor risk score with respect to time in accordance with an embodiment of the disclosure;

FIG. **7** is a graph illustrating starting profiles of a normal start and a bowed rotor mitigation sequence start in accordance with an embodiment of the disclosure;

FIG. **8** is a graph illustrating examples of various vibration level profiles of an engine in accordance with an embodiment of the disclosure;

FIG. **9** is a schematic illustration of a high spool gas path with a straddle-mounted spool in accordance with an embodiment of the disclosure;

FIG. **10** is a schematic illustration of a high spool gas path with an overhung spool in accordance with an embodiment of the disclosure;

FIG. **11** is a graph illustrating commanded starter valve opening with respect to time in accordance with an embodiment of the disclosure; and

FIG. **12** is a graph illustrating a target rotor speed profile of a dry motoring profile and an actual rotor speed versus time in accordance with an embodiment of the disclosure.

DETAILED DESCRIPTION

Various embodiments of the present disclosure are related to a bowed rotor start mitigation system in a gas turbine engine. Embodiments can include using a measured temperature value of the gas turbine engine to estimate heat stored in the engine core when a start sequence is initiated and identify a risk of a bowed rotor. The measured temperature value alone or in combination with other values can be used to calculate a bowed rotor risk parameter. For example, the measured temperature can be adjusted relative to an ambient temperature when calculating the bowed rotor risk parameter. The bowed rotor risk parameter may be used to take a control action to mitigate the risk of starting the gas turbine engine with a bowed rotor. The control action can include dry motoring, which may be performed by running an engine starting system at a lower speed with a longer duration than typically used for engine starting. Specifically, the dry motoring speed referred to herein is a speed below a major resonance speed where, if the temperatures are unhomogenized, the combination of the bowed rotor and similarly bowed casing and the resonance speed would lead to high amplitude oscillation in the rotor and high rubbing of blade tips on one side of the rotor, especially in the high pressure compressor if the rotor is straddle-mounted. The engine speed during dry motoring may oscillate within a motoring band of speed by modulating a starter valve, for example. Some embodiments increase the rotor speed of the starting spool to approach a critical rotor speed gradually according to a dry motoring profile and as thermal distortion is decreased they then accelerate beyond the critical rotor speed to complete the engine starting process.

A full authority digital engine control (FADEC) system or other system may send a message to the cockpit to inform the crew of an extended time start time due to bowed rotor mitigation actions prior to completing an engine start sequence. If the engine is in a ground test or in a test stand, a message can be sent to the test stand or cockpit based on the control-calculated risk of a bowed rotor. A test stand crew can be alerted regarding a requirement to keep the starting spool of the engine to a speed below the known resonance speed of the rotor in order to homogenize the temperature of the rotor and the casings about the rotor which also are distorted by temperature non-uniformity.

Monitoring of vibration signatures during the engine starting sequence can also or separately be used to assess the risk that a bowed rotor start has occurred due to some system malfunction and then direct maintenance, for instance, in the case of suspected outer air seal rub especially in the high compressor. Vibration data for the engine can also be monitored after bowed rotor mitigation is performed during an engine start sequence to confirm success of bowed rotor mitigation. If bowed rotor mitigation is unsuccessful or determined to be incomplete by the FADEC, resulting metrics (e.g., time, date, global positioning satellite (GPS) coordinates, vibration level vs. time, etc.) of the attempted bowed rotor mitigation can be recorded and/or transmitted to direct maintenance

During a dry motoring sequence, a starter air pressure valve can be modulated or otherwise dynamically adjusted to limit high rotor speed below high spool resonance speed and prevent rub during dry motoring operation. The bowed rotor risk parameter can also be used to limit dry motoring duration to reduce the impact on air starter turbine life. The monitoring of vibration signatures during the entire engine starting sequence can also or separately be used to assess the risk of a bowed rotor start and direct maintenance, for instance, in the case of suspected outer air seal rub especially in the high compressor.

Referring now to FIG. **1**, a schematic illustration of a gas turbine engine **10** is provided. The gas turbine engine **10** has among other components a fan through which ambient air is propelled into the engine housing, a compressor for pressurizing the air received from the fan and a combustor wherein the compressed air is mixed with fuel and ignited for generating combustion gases. The gas turbine engine **10** further comprises a turbine section for extracting energy from the combustion gases. Fuel is injected into the combustor of the gas turbine engine **10** for mixing with the compressed air from the compressor and ignition of the resultant mixture. The fan, compressor, combustor, and turbine are typically all concentric about a central longitudinal axis of the gas turbine engine **10**. Thus, thermal deflection of the components of the gas turbine engine **10** may create the aforementioned bowing or "bowed rotor" condition along the common central longitudinal axis of the gas turbine engine **10** and thus it is desirable to clear or remove the bowed condition prior to the starting or restarting of the gas turbine engine **10**.

FIG. **1** schematically illustrates a gas turbine engine **10** that can be used to power an aircraft, for example. The gas turbine engine **10** is disclosed herein as a multi-spool turbofan that generally incorporates a fan section **22**, a compressor section **24**, a combustor section **26** and a turbine section **28**. The fan section **22** drives air along a bypass flowpath while the compressor section **24** drives air along a core flowpath for compression and communication into the combustor section **26** then expansion through the turbine section **28**. Although depicted as a turbofan gas turbine engine in the disclosed non-limiting embodiment with two turbines and is sometimes referred to as a two spool engine, it should be understood that the concepts described herein are not limited to use with turbofans as the teachings may be applied to other types of turbine engines including three-spool architectures. In both of these architectures the starting spool is that spool that is located around the combustor, meaning the compressor part of the starting spool is flowing directly into the combustor and the combustor flows directly into the turbine section.

The engine **10** generally includes a low speed spool **30** and a high speed spool **32** mounted for rotation about an engine central longitudinal axis A relative to an engine static structure **36** via several bearing systems **38**. It should be understood that various bearing systems **38** at various locations may alternatively or additionally be provided.

The low speed spool **30** generally includes an inner shaft **40** that interconnects a fan **42**, a low pressure compressor **44** and a low pressure turbine **46**. The inner shaft **40** is connected to the fan **42** through a geared architecture **48** to drive the fan **42** at a lower speed than the low speed spool **30** in the example of FIG. **1**. The high speed spool **32** includes an outer shaft **50** that interconnects a high pressure compressor **52** and high pressure turbine **54**. A combustor **56** is arranged between the high pressure compressor **52** and the high pressure turbine **54**. A mid-turbine frame **57** of the engine static structure **36** is arranged generally between the high pressure turbine **54** and the low pressure turbine **46**. The mid-turbine frame **57** further supports bearing systems **38** in the turbine section **28**. The inner shaft **40** and the outer shaft **50** are concentric and rotate via bearing systems **38** about the engine central longitudinal axis A which is collinear with their longitudinal axes.

The core airflow is compressed by the low pressure compressor **44** then the high pressure compressor **52**, mixed and burned with fuel in the combustor **56**, then expanded over the high pressure turbine **54** and low pressure turbine **46**. The mid-turbine frame **57** includes airfoils **59** which are in the core airflow path. The turbines **46**, **54** rotationally drive the respective low speed spool **30** and high speed spool **32** in response to the expansion.

A number of stations for temperature and pressure measurement/computation are defined with respect to the gas turbine engine **10** according to conventional nomenclature. Station **2** is at an inlet of low pressure compressor **44** having a temperature T**2** and a pressure P**2**. Station **2.5** is at an exit of the low pressure compressor **44** having a temperature T**2.5** and a pressure P**2.5**. Station **3** is at an inlet of the combustor **56** having a temperature T**3** and a pressure P**3**. Station **4** is at an exit of the combustor **56** having a temperature T**4** and a pressure P**4**. Station **4.5** is at an exit of the high pressure turbine **54** having a temperature T**4.5** and a pressure P**4.5**. Station **5** is at an exit of the low pressure turbine **46** having a temperature T**5** and a pressure P**5**. Measured temperatures in embodiments may be acquired at one or more stations **2-5**. For example, temperature T**3** at station **3** can be used to as an engine rotor temperature measurement when there is no engine rotation. Alternatively, if available, temperature values at stations **4** (T**4**), **4.5** (T**4.5**), and/or **5** (T**5**) can be used as an engine rotor temperature. Temperature measurements can be normalized to account for hot day/cold day differences. For instance, temperature T**2** can be used as an ambient temperature and a measured temperature (e.g., T**3**) can be normalized by subtracting temperature T**2**.

Although FIG. **1** depicts one example configuration, it will be understood that embodiments as described herein can cover a wide range of configurations. For example, embodiments may be implemented in a configuration that is described as a "straddle-mounted" spool **32**A of FIG. **9**. This configuration places two bearing compartments **37**A and **39**A (which may include a ball bearing and a roller bearing respectively), outside of the plane of most of the compressor disks of high pressure compressor **52**A and at outside at least one of the turbine disks of high pressure turbine **54**A. In contrast with a straddle-mounted spool arrangement, other embodiments may be implemented using an over-hung mounted spool **32**B as depicted in FIG. **10**. In over-hung mounted spool **32**B, a bearing compartment **37**B is located forward of the first turbine disk of high pressure turbine **54**B such that the high pressure turbine **54**B is overhung, and it is physically located aft of its main supporting structure. The use of straddle-mounted spools has advantages and disadvantages in the design of a gas turbine, but one characteristic of the straddle-mounted design is that the span between the bearing compartments **37**A and **39**A is long, making the amplitude of the high spot of a bowed rotor greater and the resonance speed that cannot be transited prior to temperature homogenization is lower. For any thrust rating, the straddle mounted arrangement, such as straddle-mounted spool **32**A, gives Lsupport/Dhpt values that are higher, and the overhung mounted arrangement, such as overhung spool **32**B, can be as much as 60% of the straddle-mounted Lsupport/Dhpt. Lsupport is the distance between bearings (e.g., between bearing compartments **37**A and **39**A or between bearing compartments **37**B and **39**B), and Dhpt is the diameter of the last blade of the high pressure turbine (e.g., high pressure turbine **54**A or high pressure turbine **54**B). As one example, a straddle-mounted engine starting spool, such as straddle-mounted spool **32**A, with a roller bearing at bearing compartment **39**A located aft of the high pressure turbine **54**A may be more vulnerable to bowed rotor problems since the Lsupport/Dhpt ranges from 1.9 to 5.6. FIGS. **9** and **10** also illustrate a starter **120** interfacing via a tower shaft **55** with the straddle-mounted spool **32**A proximate high compressor **52**A and interfacing via tower shaft **55** with the overhung mounted spool **32**B proximate high compressor **52**B as part of a starting system.

Turning now to FIG. **2**, a schematic of a starting system **100** for the gas turbine engine **10** of FIG. **1** is depicted according to an embodiment. The starting system **100** is also referred to generally as a gas turbine engine system. In the example of FIG. **2**, the starting system **100** includes a controller **102** which may be an electronic engine control, such as a dual-channel FADEC, and/or engine health monitoring unit. In an embodiment, the controller **102** may include memory to store instructions that are executed by one or more processors. The executable instructions may be stored or organized in any manner and at any level of abstraction, such as in connection with a controlling and/or monitoring operation of the engine **10** of FIG. **1**. The one or more processors can be any type of central processing unit (CPU), including a general purpose processor, a digital signal processor (DSP), a microcontroller, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), or the like. Also, in embodiments, the memory may include random access memory (RAM), read only memory (ROM), or other electronic, optical, magnetic, or any other computer readable medium onto which is stored data and control algorithms in a non-transitory form.

The starting system **100** can also include a data storage unit (DSU) **104** that retains data between shutdowns of the gas turbine engine **10** of FIG. **1**. The DSU **104** includes non-volatile memory and retains data between cycling of power to the controller **102** and DSU **104**. A communication link **106** can include an aircraft and/or test stand communication bus to interface with aircraft controls, e.g., a cockpit, various onboard computer systems, and/or a test stand.

A motoring system **108** is operable to drive rotation of a starting spool (e.g., high speed spool **32**) of the gas turbine engine **10** of FIG. **1**. Either or both channels of controller **102** can alternate on and off commands to an electromechanical device **110** coupled to a discrete starter valve **116**A to achieve a partially open position of the discrete starter valve **116**A to control a flow from a starter air supply **114** (also referred to as air supply **114**) through a transfer duct **118** to an air turbine starter **120** (also referred to as starter **120** or pneumatic starter motor **120**) to drive rotation of a starting spool of the gas turbine engine **10** below an engine idle speed. The air supply **114** (also referred to as starter air supply **114**) can be provided by any known source of compressed air, such as an auxiliary power unit or ground cart.

The controller **102** can monitor a speed sensor, such as speed pickup **122** that may sense the speed of the engine rotor through its connection to a gearbox **124** which is in turn connected to the high speed spool **32** via tower shaft **55** (e.g., rotational speed of high speed spool **32**) or any other such sensor for detecting or determining the speed of the gas turbine engine **10** of FIG. **1**. The starter **120** may be coupled to the gearbox **124** of the gas turbine engine **10** of FIG. **1** directly or through a transmission such as a clutch system (not depicted). The controller **102** can establish a control loop with respect to rotor speed to adjust positioning of the discrete starter valve **116**A.

The discrete starter valve **116**A is an embodiment of a starter valve that is designed as an on/off valve which is typically commanded to either fully opened or fully closed. However, there is a time lag to achieve the fully open position and the fully closed position. By selectively alternating an on-command time with an off-command time through the electromechanical device **110**, intermediate positioning states (i.e., partially opened/closed) can be achieved. The controller **102** can modulate the on and off commands (e.g., as a duty cycle using pulse width modulation) to the electromechanical device **110** to further open the discrete starter valve **116**A and increase a rotational speed of the starting spool of the gas turbine engine **10** of FIG. **1**. In an embodiment, the electromechanical device **110** has a cycle time defined between an off-command to an on-command to the off-command that is at most half of a movement time for the discrete starter valve **116**A to transition from fully closed to fully open. Pneumatic lines **112**A and **112**B or a mechanical linkage (not depicted) can be used to drive the discrete starter valve **116**A between the open position and the closed position. The electromechanical device **110** can be a solenoid that positions the discrete starter valve **116**A based on intermittently supplied electric power as commanded by the controller **102**. In an alternate embodiment, the electromechanical device **110** is an electric valve controlling muscle air to adjust the position of the discrete starter valve **116**A as commanded by the controller **102**.

In the example of FIG. **2**, the starting system **100** also includes a vibration monitoring system **126**. The vibration monitoring system **126** includes at least one vibration pickup **128**, e.g., an accelerometer, operable to monitor vibration of the gas turbine engine **10** of FIG. **1**. Vibration signal processing **130** can be performed locally with respect to the vibration pickup **128**, within the controller **102**, or through a separate vibration processing system, which may be part of an engine health monitoring system to acquire vibration data **132**. Alternatively, the vibration monitoring system **126** can be omitted in some embodiments.

One or more temperature sensors **134**, such as thermocouples, can provide measured temperatures at associated locations of the gas turbine engine **10** to the controller **102**. For example, the temperature sensors **134** can be located at station **2** (T**2**), station **2.5** (T**2.5**), station **3** (T**3**), station **4** (T**4**), station **4.5** (T**4.5**), and/or station **5** (T**5**) as previously described with respect to FIG. **1**.

Similar to FIG. **2**, FIG. **3** is a schematic illustration of a starting system **100**A for the gas turbine engine **10** of FIG. **1** in accordance with another embodiment. The starting system **100**A includes controller **102** that controls motoring system **108**A, as an alternate embodiment of the motoring system **108** of FIG. **2**. Rather than using an electromechanical device **110** coupled to a discrete starter valve **116**A to achieve a partially open position of the discrete starter valve **116**A of FIG. **2**, the motoring system **108**A of FIG. **3** uses a variable position starter valve **116**B. In FIG. **3**, either or both channels of controller **102** can output a valve control signal **150** operable to dynamically adjust a valve angle of the variable position starter valve **116**A that selectively allows a portion of the air supply **114** to pass through the variable position starter valve **116**B and transfer duct **118** to air turbine starter **120**. The variable position starter valve **116**B is a continuous/infinitely adjustable valve that can hold a commanded valve angle, which may be expressed in terms of a percentage open/closed and/or an angular value (e.g., degrees or radians). Performance parameters of the variable position starter valve **116**B can be selected to meet dynamic response requirements of the starting system **100**A. For example, in some embodiments, the variable position starter valve **116**B has a response rate of 0% to 100% open in less than 40 seconds. In other embodiments, the variable position starter valve **116**B has a response rate of 0% to 100% open in less than 30 seconds. In further embodiments, the variable position starter valve **116**B has a response rate of 0% to 100% open in less than 20 seconds.

The controller **102** can monitor a valve angle of the variable position starter valve **116**B using valve angle feedback signals **152** provided to both channels of controller **102**. As one example, in an active/standby configuration, both channels of the controller **102** can use the valve angle feedback signals **152** to track a current valve angle, while only one channel designated as an active channel outputs valve control signal **150**. Upon a failure of the active channel, the standby channel of controller **102** can take over as the active channel to output valve control signal **150**. In an alternate embodiment, both channels of controller **102** output all or a portion of a valve angle command simultaneously on the valve control signals **150**. The controller **102** can establish an outer control loop with respect to rotor speed and an inner control loop with respect to the valve angle of the variable position starter valve **116**B. One or more temperature sensors **134**, such as thermocouples, can provide measured temperatures at associated locations of the gas turbine engine **10** to the controller **102**.

As in the example of FIG. **2**, the starting system **100**A of FIG. **3** also includes vibration monitoring system **126**. The vibration monitoring system **126** includes at least one vibration pickup **128**, e.g., an accelerometer, operable to monitor vibration of the gas turbine engine **10** of FIG. **1**. Vibration signal processing **130** can be performed locally with respect to the vibration pickup **128**, within the controller **102**, or through a separate vibration processing system, which may be part of an engine health monitoring system to acquire vibration data **132**. Alternatively, the vibration monitoring system **126** can be omitted in some embodiments.

FIG. **4** is a block diagram of a system **200** for bowed rotor start mitigation using direct temperature measurement that may control the discrete starter valve **116**A of FIG. **2** or the variable position starter valve **116**B of FIG. **3** via control signals **210** in accordance with an embodiment. The system **200** may also be referred to as a bowed rotor start mitigation system. In the example of FIG. **4**, the system **200** includes sensor processing **202** operable to acquire and condition data from a variety of sensors such as the speed pickup **122**, vibration pickup **128**, and temperature sensors **134** of FIG. **2**. Where the variable position starter valve **116**B of FIG. **3** is used, the sensor processing **202** may also provide valve angle **207** to motoring controller **208** based on the valve angle feedback **152** of FIG. **3**. In the example of FIG. **4**, sensor processing **202** provides compressor exit temperature **T3** and ambient temperature **T2** to core temperature processing **204**. Alternatively or additionally, one or more temperature values from stations **4** (T**4**), **4.5** (T**4.5**), and/or **5** (T**5**) can be provided to core temperature processing **204**. Sensor processing **202** can provide rotor speed N**2** (i.e., speed of high speed spool **32**) to a motoring controller **208** and a mitigation monitor **214**. Sensor processing **202** may also provide vibration data **132** to mitigation monitor **214**. The sensor processing **202**, core temperature processing **204**, motoring controller **208**, and/or mitigation monitor **214** may be part of controller **102**.

The heat state of the engine **10** or T_{core} is determined by the core temperature processing **204**. When the gas turbine engine **10** has stopped rotating (e.g., rotor speed N**2** is zero), the compressor exit temperature T**3** may be substantially equal to T_{core}. In some embodiments, T_{core} is set equal to T**3**-T**2** to adjust the temperature with respect to the measured ambient temperature of the gas turbine engine **10**. Further, temperature readings from other stations of the gas turbine engine **10** can be used to determine T_{core}. Communication link **106** can provide the core temperature processing **204** with an indication **205** that a start sequence of the gas turbine engine **10** has been initiated. Once rotation of the gas turbine engine **10** begins, temperature readings can be collected for a predetermined period of time, such as ten seconds. The temperature readings, e.g., T**3** or T**3**-T**2**, can be averaged as core temperature T_{core} before the temperature starts to change due to air flow from engine rotation. The core temperature processing **204** can determine a bowed rotor risk parameter that is based on the measured temperature using a mapping function or lookup table. The bowed rotor risk parameter can have an associated motoring time defining an anticipated amount of time for the motoring controller **208** to send control signals **210** to electromechanical device **110** for controlling discrete starter valve **116**A of FIG. **2** or a dry motoring profile to control valve control signals **150** for controlling variable position starter valve **116**B of FIG. **3**. For example, a higher risk of a bowed rotor may result in a longer duration of dry motoring or an extended dry motoring profile to reduce a temperature gradient prior to starting the gas turbine engine **10** of FIG. **1**.

The bowed rotor risk parameter may be quantified according to a profile curve **402** selected from a family of curves **404** that align with observed aircraft/engine conditions that impact turbine bore temperature (e.g., starting spool temperature) and the resulting bowed rotor risk as depicted in the example graph **400** of FIG. **6**.

As used herein, motoring of the engine **10** in a modified start sequence refers to the turning of a starting spool by the starter **120** at a reduced speed without introduction of fuel and an ignition source in order to cool the engine **10** to a point wherein a normal start sequence can be implemented without starting the engine **10** in a bowed rotor state. In other words, cool or ambient air is drawn into the engine **10** while motoring the engine **10** at a reduced speed in order to clear the "bowed rotor" condition, which is referred to as a dry motoring mode.

The motoring controller **208** uses a dynamic control calculation in order to determine a required valve position of the starter valve **116**A, **116**B used to supply an air supply or starter air supply **114** to the engine **10** in order to limit the motoring speed of the engine **10** to a target speed N_{target} within a motoring band or following a dry motoring profile due to the position of the starter valve **116**A, **116**B. The required valve position of the starter valve **116**A, **116**B can be determined based upon an air supply pressure as well as other factors including but not limited to ambient air temperature, parasitic drag on the engine **10** from a variety of engine driven components such as electric generators and hydraulic pumps, and other variables such that the motoring controller **208** closes the loop for an engine motoring speed target N_{target} for the required amount of time based on the output of the bowed rotor start risk model **206**. In one embodiment, the dynamic control of the valve position (e.g., open state of the valve (e.g., fully open, ½ open, ¼ open, etc.) in order to limit the motoring speed of the engine **10**) is controlled via duty cycle control (on/off timing using pulse width modulation) of electromechanical device **110** for discrete starter valve **116**A.

Referring now to FIG. **7**, a graph **450** illustrating starting profiles of a normal start **452** and a bowed rotor mitigation sequence start **454** is depicted according to an embodiment. During the normal start **452**, upon receiving the indication **205** of FIG. **4** that a start sequence of the gas turbine engine **10** has been initiated, the controller **102** of FIG. **2** opens discrete starter valve **116**A of FIG. **2** (or variable position starter valve **116**B of FIG. **3**) to enable the air supply **114** to drive rotation of starter **120** to get rotor speed N**2** of the gas turbine engine **10** up to idle speed **456**. In an embodiment, upon receiving the indication **205** of FIG. **4**, controller **102** monitors one or more temperature sensors **134** for a predetermined period of time **458** while rotor speed N**2** is at or about zero RPM. If core temperature processing **204** of FIG. **4** determines that bowed rotor mitigation is needed based on measured temperature, then bowed rotor mitigation sequence start **454** is performed instead of normal start **452**.

In the example of FIG. **7**, bowed rotor mitigation sequence start **454** oscillates the rotor speed N**2** within a motoring band **460** for a motoring time. The motoring band **460** can be defined between a starter valve close limit **462** (i.e., an upper N**2** speed limit) and a starter valve re-open limit **464** (i.e., a lower N**2** limit). In the example of FIG. **7**, the starter valve close limit **462** is about 3000 RPM and the starter valve re-open limit **464** is about 2000 RPM. The actual values used for the starter valve close limit **462** and the starter valve re-open limit **464** can be tuned to the specific performance characteristics of the gas turbine engine **10** as further described with respect to FIG. **8**.

In some embodiments, an anticipated amount of dry motoring time can be used to determine a target rotor speed profile in a dry motoring profile for the currently observed conditions. As one example, one or more baseline characteristic curves for the target rotor speed profile can be defined in tables or according to functions that may be rescaled to align with the observed conditions. An example of a target rotor speed profile **1002** is depicted in graph **1000** of FIG. **12** that includes a steep initial transition portion **1004**, followed by a gradually increasing portion **1006**, and a late acceleration portion **1008** that increases rotor speed above a critical rotor speed, through a fuel-on speed and an engine idle speed. The target rotor speed profile **1002** can be rescaled with respect to time and/or select portions (e.g., portions **1004**, **1006**, **1008**) of the target rotor speed profile **1002** can be individually or collectively rescaled (e.g., slope changes) with respect to time to extend or reduce the total motoring time. The target rotor speed profile **1002** may include all positive slope values such that the actual rotor speed **1010** is driven to essentially increase continuously while bowed rotor start mitigation is active. While the example of FIG. **12** depicts one example of the target rotor speed profile **1002** that can be defined in a dry motoring profile, it will be understood that many variations are possible in embodiments.

The example of FIG. **11** illustrates how a valve angle command **902** can be adjusted between 0 to 100% of a commanded starter valve opening to generate the actual rotor speed **1010** of FIG. **12**. As the actual rotor speed **1010** tracks to the steep initial transition portion **1004** of the target rotor speed profile **1002**, the valve angle command **902** transitions through points "a" and "b" to fully open the variable position starter valve **116**B. As the slope of the target rotor speed profile **1002** is reduced in the gradually increasing portion **1006**, the valve angle command **902** is reduced between points "b" and "c" to prevent the actual rotor speed **1010** from overshooting the target rotor speed profile **1002**. In some embodiments, decisions to increase or decrease the commanded starter valve opening is based on monitoring a rate of change of the actual rotor speed **1010** and projecting whether the actual rotor speed **1010** will align with the target rotor speed profile **1002** at a future time. If it is determined that the actual rotor speed **1010** will not align with the target rotor speed profile **1002** at a future time, then the valve angle of the variable position starter valve **116**B is adjusted (e.g., increase or decrease the valve angle command **902**) at a corresponding time. In the example of FIGS. **11** and **12**, the valve angle command **902** oscillates with a gradually reduced amplitude between points "c", "d", and "e" as the actual rotor speed **1010** tracks to the target rotor speed profile **1002** through the gradually increasing portion **1006**. As dry motoring continues, the overall homogenization of the engine **10** increases, which allows the actual rotor speed **1010** to safely approach the critical rotor speed without risking damage. The valve angle command transitions from point "e" to point "f" and beyond to further increase the actual rotor speed **1010** in the late acceleration portion **1008** above the critical rotor speed, through a fuel-on speed and an engine idle speed. By continuously increasing the actual rotor speed **1010** during dry motoring, the bowed rotor condition can be reduced faster than holding a constant slower speed.

In reference to FIGS. **4** and **12**, the mitigation monitor **214** of FIG. **4** can operate in response to receiving a complete indicator **212** to run a verification of the bowed rotor mitigation. The mitigation monitor **214** can provide mitigation results **216** to the motoring controller **208** and may provide result metrics **218** to other systems, such a maintenance request or indicator. Peak vibrations can be checked by the mitigation monitor **214** during the start processes to confirm that bowed rotor mitigation successfully removed the bowed rotor condition. The mitigation monitor **214** may also run while dry motoring is active to determine whether adjustments to the dry motoring profile are needed. For example, if a greater amount of vibration is detected than was expected, the mitigation monitor **214** can request that the motoring controller **208** reduce a slope of the target rotor speed profile **1002** of FIG. **12** to extend the dry motoring time before driving the actual rotor speed **1010** of FIG. **12** up to the critical rotor speed. Similarly, if the magnitude of vibration observed by the mitigation monitor **214** is less than expected, the mitigation monitor **214** can request that the motoring controller **208** increase a slope of the target rotor speed profile **1002** of FIG. **12** to reduce the dry motoring time before driving the actual rotor speed **1010** of FIG. **12** up to the critical rotor speed.

FIG. **5** is a flow chart illustrating a method **300** of bowed rotor start mitigation using direct temperature measurement of a gas turbine engine in accordance with an embodiment. The method **300** of FIG. **5** is described in reference to FIGS. **1-12** and may be performed with an alternate order and include additional steps. At block **302**, the controller **102** receives receive a speed input indicative of a rotor speed (e.g., N**2**) of the gas turbine engine **10**. The speed input may be directly or indirectly indicative of the rotational speed of high speed spool **32**, for instance, derived from a rotational speed of gearbox **124**, from speed pickup **122**, or another source (not depicted).

At block **304**, the controller **102** receives a measured temperature from a temperature sensor **134**. The measured temperature can be determined based on reading one or more temperature sensors **134** of the gas turbine engine **10** for a predetermined period of time when a start sequence of the gas turbine engine is initiated (e.g., based on indication **205**). The measured temperature may be adjusted with respect to a measured ambient temperature of the gas turbine engine **10** (e.g., T**3**-T**2**, T**4**-T**2**, etc.).

At block **306**, bowed rotor start mitigation can be performed using motoring system **108**, **108**A to rotate a starting spool of the gas turbine engine **10**. The controller **102** can drive motoring of the gas turbine engine **10** by controlling the motoring system **108**, **108**A to oscillate the rotor speed (e.g., N**2**) within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine **10** is initiated. The motoring band can include a range of speeds below a resonance speed of the gas turbine engine **10**. The motoring time can be associated with a bowed rotor risk parameter that is determined based on the measured temperature. Alternatively, other motoring profiles can be used, such as the target rotor speed profile **1002** for controlling starting spool speed during dry motoring.

At block **308**, based on determining that bowed rotor mitigation is complete, the controller **102** can monitor the vibration level of the gas turbine engine **10** while sweeping through a range of rotor speeds including a critical rotor speed and determine whether bowed rotor mitigation was successful prior to starting the gas turbine engine **10**. The mitigation monitor **214** may receive a complete indicator **212** from the motoring controller **208** when the motoring controller **208** has completed dry motoring, for instance, if the motoring time has elapsed. If the mitigation monitor **214** determines that the bowed rotor condition still exists based on vibration data **132** collected, the motoring controller **208** may restart dry motoring, or a maintenance request or indicator can be triggered along with providing result metrics **218** for further analysis. Metrics of attempted bowed rotor mitigation can be recorded in the DSU **104** based on determining that the attempted bowed rotor mitigation was unsuccessful or incomplete.

FIG. **8** is a graph illustrating examples of various vibration level profiles **502** of an engine, such as gas turbine engine **10** of FIG. **1**. The vibration level profiles **502** represent a variety of possible vibration levels observed before and/or after performing bowed rotor mitigation. A critical speed **510** is the speed at which a vibration peak is expected due to amplification effects of a bowed rotor condition along with other contributions to vibration level generally. A peak vibration **504** at critical rotor speed **510** may be used to trigger different events. For example, if the peak vibration **504** at critical rotor speed **510** is below a maintenance action threshold **506**, then no further actions may be needed. If the peak vibration **504** at critical rotor speed **510** is above a damage risk threshold **508**, then an urgent maintenance action may be requested such as an engine check. If the peak vibration **504** at critical rotor speed **510** is between the maintenance action threshold **506** and the damage risk threshold **508**, then further bowed rotor mitigation actions may be requested, such as extending/restarting dry motoring. In one embodiment, a maintenance request is triggered based on the actual vibration level exceeding maintenance action threshold **506** after completing an attempt of bowed rotor mitigation.

The lowest rotor vibration vs. speed in FIG. **8** is for a fully homogenized rotor, where mitigation is not necessary (engine parked all night long, for example). The next higher curve shows a mildly bowed rotor and so on. The maintenance action threshold **506** is a threshold for setting a maintenance flag such as requiring a troubleshooting routine of one or more system elements. The damage risk threshold **508** may be a threshold to trigger a more urgent maintenance requirement up to and including an engine check.

Further, as can be seen in the example of FIG. **8**, the motoring band **460** is defined for a range of N2 rotor speeds below the critical speed **510** and such that the worst case expected vibration **512** is below the maintenance action threshold **506** within the motoring band **460**. Performing motoring at a higher speed (e.g., 2000-3000 RPM) but less than the critical speed **510** can reduce the time needed for the temperature homogenization process while also avoiding vibrations reaching potentially harmful levels.

Accordingly and as mentioned above, it is desirable to detect, prevent and/or clear a "bowed rotor" condition in a gas turbine engine that may occur after the engine has been shut down. As described herein and in one non-limiting embodiment, the controller **102** may be programmed to automatically take the necessary measures in order to provide for a modified start sequence without pilot intervention other than the initial start request. In an exemplary embodiment, the controller **102** and/or DSU **104** comprises a microprocessor, microcontroller or other equivalent processing device capable of executing commands of computer readable data or program for executing a control algorithm and/or algorithms that control the start sequence of the gas turbine engine. In order to perform the prescribed functions and desired processing, as well as the computations therefore (e.g., the execution of Fourier analysis algorithm(s), the control processes prescribed herein, and the like), the controller **102** and/or DSU **104** may include, but not be limited to, a processor(s), computer(s), memory, storage, register(s), timing, interrupt(s), communication interfaces, and input/output signal interfaces, as well as combinations comprising at least one of the foregoing. For example, the controller **102** and/or DSU **104** may include input signal filtering to enable accurate sampling and conversion or acquisitions of such signals from communications interfaces. As described above, exemplary embodiments of the disclosure can be implemented through computer-implemented processes and apparatuses for practicing those processes.

While the present disclosure has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the present disclosure is not limited to such disclosed embodiments. Rather, the present disclosure can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the present disclosure. Additionally, while various embodiments of the present disclosure have been described, it is to be understood that aspects of the present disclosure may include only some of the described embodiments. Accordingly, the present disclosure is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

The invention claimed is:

1. A bowed rotor start mitigation system for a gas turbine engine, the bowed rotor start mitigation system comprising:

a controller operable to receive a speed input indicative of a rotor speed of the gas turbine engine and a measured temperature of the gas turbine engine, the controller further operable to drive motoring of the gas turbine engine by oscillating the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated, wherein the motoring time is associated with a bowed rotor risk parameter that is determined based on the measured temperature using a mapping function or lookup table with a higher risk resulting in a longer duration to reduce a temperature gradient within the gas turbine engine.

2. The bowed rotor start mitigation system as in claim **1**, wherein the motoring band comprises a range of speeds below a resonance speed of the gas turbine engine.

3. The bowed rotor start mitigation system as in claim **1**, wherein the measured temperature is adjusted with respect to a measured ambient temperature of the gas turbine engine by subtracting the measured ambient temperature.

4. The bowed rotor start mitigation system as in claim **1**, wherein the measured temperature is determined based on averaging readings from one or more temperature sensors of the gas turbine engine for a predetermined period of time when the start sequence of the gas turbine engine is initiated.

5. The bowed rotor start mitigation system as in claim **1**, wherein based on determining that bowed rotor mitigation is complete, the controller is operable to monitor a vibration level while sweeping through a range of rotor speeds including a critical rotor speed and determine whether bowed rotor mitigation was successful prior to starting the gas turbine engine.

6. The bowed rotor start mitigation system as in claim **1**, wherein the measured temperature is determined based on averaging data from one or more temperature sensors at station **3** of the gas turbine engine.

7. The bowed rotor start mitigation system as in claim **1**, wherein the measured temperature is determined based on averaging data from one or more temperature sensors at station **4** of the gas turbine engine.

8. The bowed rotor start mitigation system as in claim **1**, wherein the measured temperature is determined based on averaging data from one or more temperature sensors at station **4.5** of the gas turbine engine.

9. The bowed rotor start mitigation system as in claim **1**, wherein the controller is operable to drive motoring of the gas turbine engine by oscillating the rotor speed to continuously rotate within the motoring band for the motoring time based on the measured temperature when the start sequence of the gas turbine engine is initiated and prior to determining that bowed rotor mitigation is complete.

10. A gas turbine engine system comprising:

a motoring system operable to drive rotation of the gas turbine engine;

a speed pickup;

a temperature sensor; and

an electronic engine control operable to receive a speed input from the speed pickup indicative of a rotor speed of the gas turbine engine and a measured temperature from the temperature sensor, the electronic engine control further operable to drive motoring of the gas turbine engine by controlling the motoring system to oscillate the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated, wherein the motoring time is associated with a bowed rotor risk parameter that is determined based on the measured temperature using a mapping function or lookup table with a higher risk resulting in a longer duration to reduce a temperature gradient within the gas turbine engine.

11. The gas turbine engine as in claim **10**, wherein the motoring band comprises a range of speeds below a resonance speed of the gas turbine engine and the measured temperature is adjusted with respect to a measured ambient temperature of the gas turbine engine by subtracting the measured ambient temperature.

12. A method of bowed rotor start mitigation for a gas turbine engine, the method comprising:

receiving, by a controller, a speed input indicative of a rotor speed of the gas turbine engine;

receiving, by the controller, a measured temperature of the gas turbine engine; and

driving, by the controller, motoring of the gas turbine engine by oscillating the rotor speed within a motoring band for a motoring time based on the measured temperature when a start sequence of the gas turbine engine is initiated, wherein the motoring time is associated with a bowed rotor risk parameter that is determined based on the measured temperature using a mapping function or lookup table with a higher risk resulting in a longer duration to reduce a temperature gradient within the gas turbine engine.

13. The method as in claim **12**, wherein the motoring band comprises a range of speeds below a resonance speed of the gas turbine engine.

14. The method as in claim **12**, wherein the measured temperature is adjusted with respect to a measured ambient temperature of the gas turbine engine by subtracting the measured ambient temperature.

15. The method as in claim **12**, wherein the measured temperature is determined based on averaging readings from one or more temperature sensors of the gas turbine engine for a predetermined period of time when the start sequence of the gas turbine engine is initiated.

16. The method as in claim **12**, wherein based on determining that bowed rotor mitigation is complete, the controller is operable to monitor a vibration level while sweeping through a range of rotor speeds including a critical rotor speed and determine whether bowed rotor mitigation was successful prior to starting the gas turbine engine.

17. The method as in claim **12**, wherein the measured temperature is determined based on averaging data from one or more temperature sensors at station **3** of the gas turbine engine.

18. The method as in claim **12**, wherein the measured temperature is determined based on averaging data from one or more temperature sensors at station **4** of the gas turbine engine.

19. The method as in claim **12**, wherein the measured temperature is determined based on averaging data from one or more temperature sensors at station **4.5** of the gas turbine engine.

20. The method of claim **12**, wherein driving motoring of the gas turbine engine is performed by oscillating the rotor speed to continuously rotate within the motoring band for the motoring time based on the measured temperature when the start sequence of the gas turbine engine is initiated and prior to determining that bowed rotor mitigation is complete.

* * * * *